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APOLLO BLOCK II SPS ENGINE (AJ10-137) MOD I-D AND MOD I-E BIPROPELLANT VALVES QUALIFICATION TESTS (PHASE VI, PART III)

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K. L. Farrow, A. L. Berg, and C. E. Robinson
ARO, Inc.

April 1969

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ROCKET TEST FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE

NOTICES

APOLLO BLOCK II SPS ENGINE (AJ10-137) MOD I-D AND MOD I-E BIPROPELLANT VALVES QUALIFICATION TESTS (PHASE VI, PART III)

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FOREWORD

The work reported herein was sponsored by the National Aeronautics and Space Administration, Manned Spacecraft Center (NASA/MSC) under Program Area 921E, Project 9281.

The results of tests were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under contract F40600-69-C-0001. The testing was conducted in Propulsion Engine Test Cell (J-3) of the Rocket Test Facility (RTF) between May 10 and 15, 1968, and August 7 and 23, 1968, under ARO Project No. RM1731. The manuscript was submitted for publication on November 27, 1968.

The contents of this report are the results of an altitude qualification testing program of the Aerojet-General Corporation (AGC), Block II AJ10-137, liquid-propellant rocket engine. This testing (Phase VI, Part III) was a continuation of previous testing (Phase V, and Phase VI, Part I) during which thrust chamber bipropellant valves (TCV) did not meet qualification requirements and were subsequently modified for retesting as reported herein.

Technical liaison was provided by AGC, subcontractor of North American Rockwell, Space Division (NAR-SD) for the development of the Apollo Service Module (SM) engine. Quality assurance surveillance was provided by AGC, NAR, and ARO, Inc.

The test program was requested to support the Apollo project under MIPR-29844G.

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This technical report has been reviewed and is approved.

Donald W. Ellison
Lt Colonel, USAF
AF Representative, RTF
Directorate of Test

Roy R. Croy, Jr.
Colonel, USAF
Director of Test

ABSTRACT

Simulated altitude testing of the Apollo SPS Block II engine was conducted to qualify the latest design bipropellant valves (Mod I-D and Mod I-E), to investigate combustion overpressure during ignition, and to determine the heating rates of the flight-type electric heaters on the propellant lines and bipropellant valve. Propellants used were nitrogen tetroxide and 50/50 hydrazine/unsymmetrical dimethylhydrazine. Fifty-one test firings were made for a total of 922 sec of firing time during four test periods. Engine operation and performance were satisfactory. At the conclusion of these tests, the Mod I-E bipropellant valve was considered qualified for flight. Combustion overpressure as high as 27 percent were obtained, and the electric heaters operated satisfactorily.

CONTENTS

APPENDIXES

NOMENCLATURE

A	Area, in.^{2}
C_F	Nozzle thrust coefficient
c^*	Characteristic velocity, ft/sec
F	Force, lb_f
FS-1	Fire switch, start
FS-2	Fire switch, shutdown
g_c	Gravitational conversion factor, proportionality constant, lb_m-ft/lb_f-sec^2
I_{sp}	Specific impulse, lb_f-sec/lb_m
I_t	Total impulse, lb_f-sec
O/F	Mixture ratio, lb_m (oxidizer)/lb_m (fuel)
p	Pressure, psia
T	Temperature, ^oF
t	Time
$\dot{w}$	Propellant flow rate, lb_m/sec

SUBSCRIPTS

a	Axial
c	Chamber
cal	Calibrate
calc	Calculated
cell	Test cell ambient
e	Nozzle exit
f	Fuel
i	Initial

j	Injector
l	Line
n	Nozzle
nom	Nominal
o	Oxidizer
p	Propellant
s	Shot or individual firing
t	Throat, total, tank
V	Bipropellant valve
v	Corrected to vacuum
x,y,z	Coordinates

SECTION I
INTRODUCTION

The Apollo spacecraft consists of a Command Module (CM, three-man capsule), Service Module (SM) which contains the main propulsion system and propellant tankage, and the Lunar Module (LM). The AJ10-137 is the main propulsion engine installed in the SM.

Three phases of simulated altitude testing were conducted to develop and qualify the Block I engine (Refs. 1 through 10), but difficulties encountered during altitude testing resulted in a redesigned engine designated Block II which was subjected to further development tests (Phase IV, Refs. 11 and 12) and qualification tests. The Block II engine was qualified during Phase V testing (Ref. 13) except for the thrust chamber bipropellant valve (TCV), which developed leaks slightly greater than the specified limits.

Phase VI was initiated primarily for qualification testing of the redesigned TCV designated Mod I-C. However, other TCV modifications and test objectives were incorporated during the conduct of the test program. A chronological listing of the TCV types and the corresponding AEDC technical reports for Phase VI is presented below:

Valve Type, Listed Chronologically as Tested	Primary Test Objectives	AEDC Technical Report Designation
Mod I-C	Qualify Mod I-C TCV, investigate postfire propellant evaporative cooling of the injector, evaluate TCV and propellant line heaters.	AEDC-TR-68-178 Phase VI, Part I (Ref. 14)
Mod I-D	Qualify TCV Mod I-D, evaluate TCV and propellant line heaters, preliminary investigation of combustion overpressure.	Phase VI, Part III (This report)
Mod I-D	High priority investigation of combustion overpressure.	AEDC-TR-68-273 Phase VI, Part II (Ref. 15)
Mod I-E	Qualify Mod I-E TCV	Phase VI, Part III (This report)

During the testing reported in Ref. 14, the Mod I-C TCV also developed leaks slightly in excess of the specified limits. Subsequently, a Mod I-D TCV was provided to AEDC for qualification testing, but an indication of combustion overpressure during engine ignition was detected during a concurrent Apollo flight which required immediate investigation. Therefore, the Mod I-D valve qualification test plan was amended to include preliminary ignition characteristics tests. Since the preliminary ignition tests were inconclusive, a more thorough investigation was conducted (Ref. 15) which had priority over the completion of TCV qualification testing. During both ignition test series, the Mod I-D TCV actuation was sluggish at temperatures near $30^{o}F$, requiring the development of the Mod I-E valve for final TCV qualification testing.

This report covers the Mod I-D and Mod I-E TCV qualification tests conducted in Propulsion Engine Test Cell (J-3). Test results include a discussion of TCV operation and leakage rates; engine combustion overpressure data during ignition, TCV, and engine propellant line electric heater evaluation; and test article durability. Engine transient and steady-state performance is also presented as supplementary information.

One engine assembly was tested using two TCV assemblies for a total operating time of 922 sec during four test periods. A summary of the firings by test period is presented in Table I (Appendix II).

SECTION II
APPARATUS

2.1 TEST ARTICLE

The Aerojet AJ10-137 rocket engine is a pressure-fed, liquid-propellant engine which includes a self-contained nitrogen-pressure-actuated bipropellant valve, a doublet impingement injector, a film-cooled ablative combustion chamber, electric gimbal actuators, and a 62.5 area ratio radiation-cooled nozzle extension. The overall height of the complete engine assembly is approximately 13 ft (Fig. 1, Appendix I), and the engine assembly weighs approximately 850 lb.

The Block II engine used for this testing was designed to operate at a nominal 1.60 mixture ratio (O/F) and a chamber pressure of 99 psia with a minimum of 50 starts over an operating life of 750 sec. The liquid, storable,

hypergolic propellants were nitrogen tetroxide (N_2O_4) as the oxidizer (MSC-PPD-2A) and Aerozine-50® (AZ-50) as the fuel (MIL-P-27402). The N_2O_4 had a nominal 0.6 percent by weight nitric oxide additive.

During Phase VI testing, gimbal actuators were not included in the engine assembly; engine gimbal movement was restrained by fixed mechanical linkage. The radiation-cooled nozzle extension was attached to the combustion chamber at the 6:1 area ratio. The major components used in each engine assembly are identified as follows:

Engine S/N	Test Period	TCV S/N	Injector S/N	Chamber S/N	Nozzle Extension S/N	Balance Orifices
54G	FK, FL	122(Mod I-D)	094	352	052	Dual Bore
54H	FP, FQ	126(Mod I-E)	094	352	052	Dual Bore

2.1.1 Thrust Chamber Valve (TCV) and Propellant Lines

The Block II TCV is a pneumatic, pressure-operated, bi-propellant valve. Gaseous nitrogen stored in two spheres at pressures up to 2500 psia and regulated to approximately 220 psia provided actuation pressure. Electrical command signals were required for opening and closing the valve.

The TCV assembly consisted of eight ball valves: two in each of two parallel fuel passages and two in each of two parallel oxidizer passages (Fig. 2). One fuel passage and one oxidizer passage constituted an independent valve bank; thus the TCV had two valve banks, designated banks A (lower) and B (upper). The redundant valve banks allowed normal engine operation if one of the banks became inoperative. Complete redundance in the TCV was provided; each of four TCV actuators operated one fuel and one oxidizer ball valve, and one of two nitrogen spheres and regulators provided pressure for operation of each valve bank. Each of the two independently controlled solenoid-operated enable valves was connected to a pair of actuators; thus, valve bank A, bank B, or both banks (dual bore) could be utilized to operate the engine.

The TCV was connected to the propellant supply system by the engine propellant lines. The propellant line inlets contained flexible bellows sections, to permit engine gimbaling, and screen filters. The TCV was connected to the injector by the propellant headers which were integral parts of the injector.

Trim orifices were installed at the TCV inlet ports to balance the pressure losses in the parallel valve passages so that engine operation would be unaffected by choice of valve bank. Engine balance orifices were installed at the engine propellant line inlets (interfaces) to adjust the overall engine pressure losses so that nominal engine performance would result from standard inlet conditions of propellant pressure and temperature. Orifices for all test periods were sized for a target dual-bore balance as follows:

			Orifice Diameter, in.					
			TCV Trim				Engine Balance Interface	
Test Period	Engine S/N	TCV S/N	Bank A Ox	Bank A Fuel	Bank B Ox	Bank B Fuel	Ox	Fuel
FK, FL	54G	122	1.733	1.548	1.720	1.930	2.047	1.407
FP	54H	126	1.685	1.548	1.672	1.930	2.039	1.412
FQ	54I	126	1.930	1.548	1.930	1.930	1.781	1.382

In addition to the design changes to multiple ball seals and one-piece ball shafts which had been instituted for the previously tested Mod I-C design (Ref. 14), the Mod I-D design included some design improvements of the ball seals and seal mounts (Fig. 3). The No. 1 seal spring cartridge (fuel and oxidizer) was changed to be similar to the No. 3 cartridge which had demonstrated better test reliability than the No. 1 cartridge. The seals were made of BF-1 material, a glass-reinforced Teflon® intended to extend the cycle life by increasing resistance to creep and scoring. The oxidizer ball shaft seals and assembly parts were changed for improved shaft seal performance. The shaft seal drain manifolds (fuel and oxidizer) incorporated some design changes to eliminate any shaft seal leakage into the valve gear box. The actuator shaft idler roller material was changed from Delrin® to stainless steel to prevent failure should oxidizer vapors enter the gearbox (Fig. 4). The gearbox was vented with hollow tie bolts.

The Mod I-E configuration incorporated additional design changes. The actuator piston (Fig. 4) material was changed from Delrin to aluminum (with a Delrin guide ring) to minimize differential thermal expansion between the piston and cylinder (which had permitted excessive actuation nitrogen leakage past the piston at temperatures near 30°F). Actuator O-ring material, size, and installation design changes were made to improve sealing. The fuel ball shaft seals and drain manifold seals were changed to facilitate installation and to improve reliability.

2.1.2 Electric Heaters

Dual-element electric strip heaters were bonded to a portion of the F-3 fixture lines, to the engine propellant lines, and to the bottom surface of the bipropellant TCV for test periods FK and FL. The heaters, provided by NAR, were installed on the engine under the direction of NAR as shown in Fig. 5.

The F-3 fixture propellant line heaters, which were used to reduce engine line conduction losses, extended upstream approximately 3 ft from the engine interface. The flight-type engine propellant line heaters extended from the engine interface to the TCV flange, splitting in order to cover both TCV inlet manifold passages. Two strips approximately 1 in. wide, each containing two heating elements, were bonded 180 deg apart along each propellant line. The F-3 fixture line and engine lines with the heaters attached were insulated with 30 layers of 0.00035 ±0.00015-in.-thick aluminized Mylar® superinsulation. The TCV heater pad was also flight-type hardware. Two independent series circuits were provided, each containing one element of the F-3 fixture line, engine line, and TCV pad heaters. The two circuits A and B (not related to TCV banks) could be used separately or simultaneously; each circuit provided half the total heating capacity.

The power distribution was as follows:

Circuit Designation	Power Distribution, watts F-3 Fixture Lines (Non-Flight-Type)	Engine Lines (Flight-Type)	TCV (Flight-Type)
Fuel A	9.8	18.8	15.0
Fuel B	9.8	18.8	15.0
Oxidizer A	9.8	18.8	15.0
Oxidizer B	9.8	18.8	15.0

2.1.3 Propellant Injector

Injector S/N 094 used during this testing was the standard Block II flight design (Mod 4) as tested previously at AEDC (Refs. 13, 14, and 15).

2.1.4 Combustion Chamber

The ablatively cooled combustion chamber was the standard Block II design as used previously (Ref. 13). Chamber S/N 352 was used for all tests reported herein.

2.1.5 Exhaust Nozzle Extension

The radiation-cooled nozzle extension was the same standard Block II flight design (columbium-titanium configuration) used previously (Phase V, Ref. 13). Nozzle S/N 052, used during this testing, had been tested previously for a total of 2262 sec (Ref. 13); it was used for 922 sec during this phase, resulting in a total of 3184 sec of engine firing time.

2.2 INSTALLATION

The F-3 fixture and AJ10-137 engine were installed in the Propulsion Engine Test Cell (J-3), a vertical test cell for testing rocket engines at pressure altitudes of approximately 115,000 ft (Fig. 6 and Ref. 16). A 40-ft-high by 18-ft-diam aluminum test cell capsule lined with thermopanels to permit temperature conditioning of the cell was installed over the test article and the fixture to form the pressure-sealed test chamber.

The F-3 fixture was a heavy-duty model of the Apollo SPS propellant system which was designed and built by NAR to reproduce the hydrodynamics of the SM spacecraft as closely as practical for ground testing. The spacecraft "zero-g" cans and propellant utilization system were not available for this program. The internal size and shape of the propellant tanks were identical to those of the spacecraft, and the propellant supply line configuration was identical except for modifications necessitated by ground testing requirements. The Block II tandem arrangement of two tanks was used for each propellant, a 1050-gal sump tank and a 1310-gal storage tank. A schematic diagram of the F-3 fixture is presented in Fig. 7.

A rigid cage structure was installed inside the F-3 fixture, and another inner cage was installed inside the rigid cage. The inner cage was attached to the rigid cage by means of flexure assemblies to permit axial force measurements (Fig. 8). The engine was mounted inside the inner cage.

Two heat shields were installed to protect instrumentation, plumbing, and the F-3 fixture from the nozzle extension thermal radiation. One was a facility shield with black Teflon® retained on a sheet steel structure by a steel screen. The second was an NAR-supplied, flight-type, stainless steel shield attached to the combustion chamber/nozzle extension interface.

Pressure altitude was maintained before and after test engine firings with a steam-driven ejector which was located in the test cell exhaust duct and was connected in series with the facility exhaust compressors. During the steady-state portion of a firing, pressure altitude was maintained with a supersonic engine exhaust-gas diffuser (Fig. 6).

Additional test facility systems included ground level propellant storage tanks; helium storage and regulation for F-3 propellant tank pressurization; gaseous nitrogen for test article purging, leak checking, and valve operation; and heat exchangers for temperature conditioning of propellants and test cell capsule. Equipment for test article operation located in the J-3 control room included the AGC firing console and combustion stability monitor (CSM).

2.3 INSTRUMENTATION

Instrumentation was provided to measure engine axial force, chamber pressure, temperatures, and accelerations; propellant system pressures, temperatures, and flow rates; and test cell pressures, wall temperatures, and air temperatures. All TCV leakage rates were measured by a water displacement meter. Instrumentation locations are shown in Figs. 7 through 9. Depending on the purpose of the individual parameters, the conditioned instrumentation signals were recorded variously (1) in frequency form on magnetic tape, (2) in digital form on magnetic tape, (3) in analog or frequency form on light-beam oscillographs, and (4) in analog form on indicating/recording null-balance-potentiometer recorders with direct-inking paper strip charts.

2.3.1 Pressures

Propellant and test cell pressures and thrust chamber pressure for test periods FP and FQ were measured with strain-gage-type transducers. For test period FL, thrust chamber pressure was measured with a water-cooled variable-capacitance-type transducer which was inserted directly into the standard injector tap location for improved transient response. Test cell pressure was also measured with two variable-capacitance-type precision pressure transducers.

All transducers were laboratory calibrated for this test program with traceability to the National Bureau of Standards (NBS).

2.3.2 Temperatures

Thermocouples were used to measure exterior surface temperatures of the combustion chamber, nozzle extension,

injector, TCV, propellant lines, and test cell walls. Thermocouple probes were used to measure propellant temperatures and test cell air temperature. In addition, propellant temperatures were measured with resistance temperature transducer (RTT) immersion probes, which were laboratory calibrated with traceability to the NBS. The RTT devices were also used to measure temperatures of the injector outer rim and the combustion chamber throat outer surface.

2.3.3 Axial Force

Axial force (F_a, Fig. 8) was measured with a dual-bridge, strain-gage-type load cell with a rated capacity of 30,000 lb_f. The calibration load cell and data load cell were laboratory calibrated prior to installation with traceability to the NBS. In-place calibration was accomplished with a hydraulically actuated, axial loading system containing the calibration load cell ($F_{a_{cal}}$, Fig. 8).

During test periods FL and FQ, the fixed mechanical links (which replaced the gimbal actuators) included load cells to measure the pitch and yaw forces. During test period FQ, the pitch and yaw load cells were removed, and the actuators were replaced with solid stiff links.

2.3.4 Propellant Flow Rates

Propellant flow rate measurement was accomplished with one flowmeter in each F-3 fixture propellant feedline upstream of the engine interface (Fig. 7). The flowmeters were turbine-type, axial-flow, volumetric flow sensors with two induction coil signal generators. The flowmeters were calibrated in place with propellants. The calibration techniques are presented in Ref. 17.

SECTION III
PROCEDURE

3.1 TEST ARTICLE BUILDUP AND HANDLING

Engine components shipped to AEDC for testing had propellant and pneumatic systems internal surfaces in Level I clean condition (Ref. 18). Engine S/N 54G was assembled in the RTF, Class 10,000, Clean Room (Ref. 16). Engine assembly was the responsibility of AGC. Engine buildup was conducted by ARO, Inc., under the supervision of AGC engineering and quality control personnel. After engine assembly and documentation were completed, the engine was inspected and

accepted by ARO, Inc. The engine was then the responsibility of ARO, Inc., until completion of testing.

Prior to installation, the ablative combustion chamber was weighed, and diameter measurements of the chamber throat and nozzle extension exit were made. The TCV, propellant lines, and thrust chamber were leak checked, and the TCV was functionally checked. The TCV leak check procedure is presented in Appendix III. Prior to test periods FK and FL, heaters and insulation were installed on the propellant lines and the TCV body. After completion of test periods FL and FQ, the engine was moved from the test cell to the clean room facilities for maintenance and TCV leak tests.

All test hardware was installed and all testing activities were conducted using written procedures. Quality control was maintained throughout this program to ensure that proper procedures were used and that documentation of all activities was accomplished. Surveillance was provided by AGC, NAR, and ARO, Inc.

3.2 INSTALLATION

During installation of the engine in the test cell, leak checks of the facility and F-3 fixture plumbing were performed. Checkout of the instrumentation was performed. The propellant flowmeters were calibrated in the test configuration using propellants as the flowing media, and propellant samples were taken to verify that the propellants met the applicable specifications for cleanliness and chemical assay. Mock firings were conducted to ensure that all automatically sequenced events occurred and that the TCV operated satisfactorily. Propellants were pumped from the ground storage tanks to the F-3 fixture tanks in the test cell and were sampled for cleanliness. Propellants cleanliness requirements for this test (Ref. 18) specify that no particles larger than 500 microns or fibers larger than 50 by 1500 microns shall be present in the propellants. This cleanliness requirement was met by recirculating propellants through facility filters before each test period. Calibrations of all instrumentation were completed at atmospheric pressure. Prior to each test period, the propellants and test cell capsule were temperature conditioned.

3.3 TESTING

The test cell was closed and evacuated to approximately 0.4 psia using the facility exhaust compressors. Altitude calibrations of the instrumentation were conducted, and

propellants were bled into the engine. A steam ejector was then used to further reduce test cell pressure to approximately 0.1 psia, final temperature conditioning was accomplished with the engine electric heaters or cold nitrogen purges, and the engine was fired.

All firing durations of 1.1 sec or less were controlled using the AGC firing console. Longer-duration firings were initiated and terminated by the facility sequencer. The TCV banks were selected manually before or during the firing, as required, from the AGC firing console. All other firing operations within 60 sec of firing initiation and for 30 sec after engine shutdown were controlled automatically by the facility sequencer.

After each firing, the temperatures of the test article were recorded, and a few critical temperatures were monitored in the control room.

For test periods longer than 12 hr, additional propellant samples for cleanliness determination and additional altitude calibrations were taken approximately midway through the test period.

After the final firing of test period FL, the injector and TCV were purged with GN_2 and then aspirated at test cell altitude pressure to expel propellant vapors. Whenever test cell pressure was above 0.25 psia, a trickle purge of GN_2 was supplied to the injector oxidizer header to provide a dry gas barrier between the TCV and the ambient cell atmosphere. After the final firings of test periods FP and FQ, the dry GN_2 trickle purge was used, but the TCV was not cycled prior to inspections of the downstream TCV ball surfaces. The post-FQ test period leak checks were performed without TCV cycling after the last firing. A special draining and aspirating procedure[1] was used to clean the propellant supply lines after these test periods to facilitate

[1]The procedure consisted of: (1) aspirating the injector and manifolds up to the TCV at a maximum pressure of 0.25 psia for a predetermined period, (2) activating the oxidizer injector low volume GN_2 purge, (3) operating the TCV to open the upstream oxidizer and the downstream fuel balls, (4) draining and aspirating the propellant lines (oxidizer and fuel) and TCV oxidizer passages from upstream of the TCV while simultaneously aspirating the TCV fuel passages through the injector, and (5) avoiding any further cycling of the TCV until inspection and leak checks.

investigation of ammonium nitrate salt formations (which were discovered in the TCV passages during other J-3 tests of this engine) and to avoid damaging the TCV ball seals by cycling in the event that salts had formed on the sealing surfaces.

SECTION IV
RESULTS AND DISCUSSION

4.1 GENERAL

This testing was conducted primarily to qualify a bipropellant thrust chamber valve for spacecraft use. A Mod I-D and a I-E TCV were tested at the extremes of the design envelopes for durability and functional adequacy under conditions simulating spacecraft usage. In addition, an investigation (preliminary to Ref. 15) of combustion overpressure during the ignition transient was conducted, and the heating effect of the electric flight-type heaters for the propellant lines and TCV was evaluated. The results of these tests are presented in the following sections. Overall test article durability is discussed briefly.

4.2 TCV QUALIFICATION

4.2.1 General

The TCV qualification criteria are contained in the qualification test specification (Ref. 18) and consist basically of limits for actuation times and leakage rates. The specification requirements are given in the following sections where the specific functions or components are discussed.

Engine performance was determined during this investigation primarily to ensure that the performance was not affected by the latest TCV design changes. Engine performance was satisfactory; the data are presented and discussed in Appendix IV for reference.

4.2.2 TCV Leakage

Leakage checks of the TCV were conducted both before and after testing to ascertain that the valve met the applicable specifications. Also, special leakage checks were conducted randomly to investigate specific problem areas. Leakage of the TCV actuation GN_2 system as well as propellant leakages with the TCV both open and closed were investigated.

4.2.2.1 Propellant Seals

Each TCV bore contains two balls and each ball has an upstream and a downstream seal. The seals are numbered consecutively in the direction of flow; i.e., seal No. 1 is the upstream seal on the upstream ball; seal No. 4 is the downstream seal on the downstream ball (see Fig. 3). Both pretest and posttest TCV ball and ball shaft seal leakage rates using GN_2 as the pressurant are included in Table II. Leakage rates are shown for four differential pressures across the seals in the designed sealing direction.

The shaft seal leakage rates shown are for sets of two seals with the balls in the closed position and for all four seals on a particular propellant side with the balls open. The ball seal and ball shaft seal data for the Mod I-D TCV were all within the specifications.

The posttest leakage rate of the number three seal (upstream seal of the downstream ball) of the upper oxidizer bore in the Mod I-E TCV was 48,900 cc/hr, exceeding the 10,000 cc/hr specification. All other propellant seals were found to be within the specification. The Mod I-E TCV was not disassembled and inspected internally at AEDC after test period FQ; however, it was reported after disassembly and inspection at AGC that the lip of the seal apparently had been cut by the lip of the rotating valve ball. It was further reported by AGC that the Mod I-E valve was deemed to have qualified for flight. (Attempts to reproduce the failure were unsuccessful.)

4.2.2.2 Actuation Gas Seals

As discussed in Section 2.1.1, each of the four sets (one oxidizer and one fuel per set) of TCV balls is opened by a pneumatic piston and cylinder through a rack and pinion gear (Fig. 4). The piston moves to the open position under a GN_2 pressure of from 190 to 230 psig against a spring which closes the valve when the actuation pressure is released. A quantity of gas is used from the GN_2 TCV actuation system reservoir during each valve cycle. The GN_2 volume in the actuation system is designed to allow 50 valve cycles plus system leakage.

Actuation system supply tank (sphere) pressures as a function of valve cycles for the Mod I-D and Mod I-E TCV's are shown in Fig. 10. Because of the 30 to 110°F range of hardware temperature, it was necessary to correct the Mod I-E tank pressure data to a nominal 70°F by using perfect gas relationships to reveal the trend. The average pressure decay per actuation for each bank of both valves is shown below:

	Upper Bank (B) psi/actuation, average	Lower Bank (A) psi/actuation, average
Mod I-D, S/N 122 (15 actuations)	52	93
Mod I-E, S/N 126 (30 actuations)	40	36

It is seen in Fig. 10 that pressure decays as large as 300 psi/actuation were experienced by the lower bank (A) of the Mod I-D valve which contributed to the large (93 psi/actuation) average decay rate shown above.

At the conclusion of test period FL, when the Mod I-D TCV was cycled for purging and aspirating of the propellant supply lines (see Section 3.3), the "A" actuation system sphere bled from 1000+ psig to atmospheric pressure, indicating a leak in the actuation system. It was subsequently discovered that, after removing the TCV from the engine, temperature conditioning the TCV to approximately 20°F, and performing special functional and leakage checks, the actuator piston seals and actuator piston shaft seals leaked excessively with the piston in intermediate positions. The leakage rates are shown in Table III as a function of percentage of "full open" for each piston. (An identical check was made on the Mod I-E valve after test period FQ except that it was conducted at ambient temperature. These data are also shown in Table III.) The specification leakage rates (Ref. 18) of the actuator pistons and actuator piston shaft seals are 100 cc/hr each with the piston "full open."

The A and B sphere pressure histories using the Mod I-E TCV for the 19 FQ firings conducted at the nominal 30°F hardware temperatures (Fig. 10b) indicate no excessive pressure decay because of leakage when compared with the Mod I-D TCV sphere A pressure history (Fig. 10a) for the same number of actuations. The modifications to the Mod I-D TCV (see Section 2.1.1) which resulted in the Mod I-E TCV were directed, primarily, at correcting the high leakage rates of the actuation GN_2 past the actuator piston and piston shaft seals for the lower hardware temperatures. Therefore, it was concluded that the difficulty experienced with actuator leakage for hardware temperatures near 30°F was corrected.

4.2.3 Thrust Chamber Valve Operating Times

The TCV operating times for each valve actuation were obtained from potentiometer signals recorded on light-beam oscillograms. The average operating times and the maximum

deviations from the averages as measured during test series FL and FQ are presented in Table IV.

The Mod I-D TCV operating times were erratic. Twelve of the twenty firings were found to have at least one set of ball valves operating outside the specification times for "full open," and six firings had at least one set out of specification for "full closed." Valve sets 1 and 4 were slow acting both opening and closing, whereas valve set 3 tended toward operating times faster than specification. The slow operating time of valve set 4 can be attributed in part to excessive No. 4 actuator GN_2 leakage (see Section 4.2.2.2). The Mod I-E valve operating times were all within specification.

For all firings of both TCV's, when the firing duration was sufficiently long to allow all four valve sets to open fully, the "full open" times for valve sets 1 and 4 exceeded those of valve sets 2 and 3 by greater than 100 msec, thereby meeting the specification requirements (Ref. 18).

Valve operating times were longer at the lower TCV temperatures. For those firings using 30 to 35°F propellants as compared with the 110 to 115°F propellant temperature firings, the average opening times for the Mod I-E valve sets 1 through 4 were 90, 70, 80, and 145 msec longer, respectively, whereas the closing times were 28, 35, 40, and 40 msec longer, respectively.

4.2.4 Thrust Chamber Valve Salting

After test period FL, ammonium nitrate deposits were found in the TCV downstream bores on both the oxidizer and fuel sides. The deposits on the oxidizer side, however, were considerably heavier than on the fuel side. Two crescent-shaped deposits were found at the 10 and 2 o'clock positions on the lower oxidizer downstream ball (Fig. 11). Cycling of the TCV with salt deposits on the ball surfaces is believed to have contributed to the high posttest leakage rates past the ball seals of the Mod I-D TCV (Section 4.2.2.1).

The formation of ammonium nitrate salts in the TCV posed two problems: (1) if the salt formation was the result of AZ-50 fumes diffusing into the oxidizer passages through the injector after engine shutdown, then this condition could exist in space, and each time the TCV was cycled the TCV leakage rate would increase as a result of the abrasive action of the salts on the ball seals; (2) if the salts were forming as a result of water from the test facility diffuser blowback at engine shutdown or from high humidity air entering the oxidizer passages (conditions which could not exist in space),

the cycling of the TCV during propellant supply system cleaning after a test period could still damage the TCV seals and invalidate a posttest leakage check. In an effort to determine the cause of the salting and to provide a valid TCV posttest leak check, the postfire extended altitude coast procedure described in Section 3.4 was implemented after test periods FP and FQ.

Post-FP inspections of the TCV revealed aluminum (not ammonium) nitrate deposits in the upstream oxidizer bores (see Fig. 12). No deposits were found in the downstream bores or on the balls. Since only one 30-sec firing was made, no leakage tests were conducted after the FP test series. No salt deposits were found in the TCV after test period FQ.

It was concluded that the heavy deposits of ammonium nitrate found on the downstream oxidizer balls following test period FL were the result of high humidity air entering the oxidizer passages through the injector. The formation of these deposits on the balls and subsequent operation of the TCV probably contributed to the high (but within specification) leakage rate past the lower oxidizer No. 4 seal (Table II) during the post-FL leak checks of the Mod I-D TCV.

4.3 COMBUSTION OVERPRESSURE

An investigation of combustion overpressure[2] during ignition was one of the objectives of the FL test period. An AGC-supplied, high-frequency-response, water-cooled Photocon® transducer (Model 307) was installed for the measurement of chamber pressure. Both pretest and posttest in-place calibrations of the transducer were conducted with 0.4-percent (3σ) agreement at the operating level, but the steady-state test data were found to be approximately 10 percent low. The reason for this anomaly is not known. Because the transients and ignition peaks are believed to be low by the same percentage as the steady-state levels over the short duration of a single firing, the overpressure data are considered valid and are presented in Table V. Data from firings FL-03 and -06 are not included because the firing durations were too short to establish a steady-state base line. Data from firing FL-01 are not included because of recording difficulties.

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[2]Combustion overpressure is defined as a thrust chamber pressure that exceeds the steady-state operating level during the ignition transient and is expressed as a percentage of the steady-state level.

The overpressures ranged from 7 to 28 percent above the steady-state operating levels. Generally, the dual-bore (AB) firings resulted in higher overpressures than the single bore. The dry-bore[3] firings also tended toward higher overpressures than the wet bore.

Typical chamber pressure histories for dry-, wet-, single-, and dual-bore ignitions are shown in Fig. 13. All firings have a preignition spike which is a characteristic of the AJ10-137 engine. As would be expected, the dual-bore firings ignite before the single-bore firings. The faltering ignition of the single-bore (wet) firing is characteristic of all single-bore firings whether wet or dry with very few exceptions (one of which is firing FL-09A, also included in Fig. 13).

Because the scope of this overpressure investigation was quite limited and because the results were somewhat inconclusive, a more thorough investigation was conducted subsequently and is reported in Ref. 15.

4.4 FLIGHT HEATER EVALUATION

The flight vehicle will utilize low-power electric heaters to avoid excessively low temperatures in the engine propellant supply lines and TCV during the long coast periods in space. Flight-type heaters were installed on the engine during test periods FK and FL. The effectiveness of these heaters was evaluated by activating first a single circuit (test period FK) and then both circuits (test period FL) while monitoring test article temperatures. The conditions established prior to beginning the heater tests were:

1. Test cell pressure a maximum of 0.25 psia.
2. Propellants in the lines up to the upstream TCV balls.
3. Internal TCV, propellant line, and injector temperatures stabilized between 25 and 35°F.

4.4.1 Single Circuit Performance

Temperature histories of the engine propellant lines with only one heater circuit energized are shown in Fig. 14.

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[3] Dry bore is defined as an absence of propellants between the upstream and downstream TCV balls, a condition which occurs only for the first ignition of the engine.

The fuel line temperature rise averaged approximately 4°F/hr during the first 2 hr. The oxidizer A circuit was found to be inoperative after 1.28 hr, and the B circuit was energized. The effect of turning on an operable heater circuit is evident; however, no definitive heating rate could be established. By assuming that the heat input to the oxidizer line is equal to that of the fuel line, the heating rate of the oxidizer line should be approximately 4.5°F/hr.

Internal TCV temperature histories are shown in Fig. 15. The TCV temperature on the fuel side increased an average of from 11 to 12°F after the first 2 hr of single circuit heating. The effect of the failed A circuit on the oxidizer side is again quite evident in Fig. 15b; however, a slight temperature rise was noted during the initial 1.28 hr, which was the result of conduction from the fuel side. As would be expected, the temperature in the lower set of TCV balls, which are closest to the heater pad, rose more quickly and to a higher level than those in the upper set.

4.4.2 Double Circuit Performance

Temperature histories of the engine propellant lines with both heater circuits energized are shown in Fig. 16. Thermocouples T_{plf-3} and T_{plo-3} reacted very quickly to heat input showing a 10 to 14°F rise in only 0.17 hr (10 min) but thereafter indicating a rise rate of approximately 7°F/hr which compares well with the rise rate of the remaining two temperatures shown in Fig. 16. It is suspected that thermocouples T_{plf-3} and T_{plo-3} sensed primarily heater element temperature instead of propellant line temperature and that a propellant line temperature rise rate with both heater circuits energized of approximately 7°F/hr is realistic. Further, a rise rate of 7°F/hr with both heater circuits operating compares well with the single circuit rise rate of from 3 to 4°F/hr shown in Fig. 14.

Internal TCV temperature histories are shown in Fig. 17. The average temperature rise during 1 hr of dual-heater operation was 19°F as compared with 9°F for the first hour of single circuit operation.

4.5 TEST ARTICLE DURABILITY

4.5.1 Chamber Wall Temperature

The temperature histories of the thrust chamber outside wall at the throat and the injector attachment flange for the 550-sec firing (FQ-19) and the subsequent coast period are

shown in Fig. 18. The specification maximum temperature is also shown (Ref. 18), assuming a 35°F ambient and test article temperature.

At the conclusion of the 550-sec firing, the thrust chamber had been fired for a total of 740 sec. The prefire throat temperatures of from 140 to 160°F are the result of heat soakback from firing FQ-18, which was 10 sec in duration and was conducted 4 hr and 47 min prior to FQ-19. The residual heat in the ablative chamber material from the FQ-18 firing plus the heat added during firing FQ-19 was sufficient to exceed the specification outer wall temperatures. It can be seen by zero-shifting the pre-FQ-19 levels of T_{ct-1} and T_{ct-2} to 35°F that the outer wall temperatures would not have exceeded the specification if firing FQ-19 had been the initial firing of the series.

4.5.2 Nozzle Extension Cracks

During test period FQ, the nozzle extension skirt (S/N 052) separated from the chamber attachment flange around approximately 60 deg of the circumference (Fig. 19) Several 1-in.-long longitudinal cracks in the columbium section of the extension at the 40:1 area ratio stiffener appeared during the previous FL test period but showed little if any progression during the FP and FQ series.

It should be noted that, at the beginning of the FQ test series, the extension had already been fired for a duration equal to three times the 750-sec design life of the engine, and therefore the failure constitutes no inadequacy in the component.

4.5.3 Fuel Interface Screen Failure

Damage to the fuel interface screen was discovered during post-FL test period inspections (Fig. 20). High-magnification inspection of the damaged area suggested metal fatigue in the screen at the area of the weld joint to the star-shaped stiffener. Similar, but more severe, damage occurred in the fuel strainer used during testing of engine S/N 055 (Ref. 15).

SECTION V
SUMMARY OF RESULTS

The significant results of testing the AJ10-137 engine to qualify the thrust chamber valve (TCV), to investigate combustion overpressure during ignition, and to determine the

heating effects of the flight-type electric propellant line and TCV heaters are summarized below:

1. The Mod I-E TCV, which incorporated modifications to correct excessive actuation gas leakage at low temperatures, met the applicable actuation gas leakage specification. The Mod I-E posttest leakage rate of the No. 3 propellant ball seal in the upper oxidizer bore exceeded the specification but was judged acceptable by AGC, NAR, and NASA. Therefore, the Mod I-E TCV was qualified for flight.

2. All operating times for the Mod I-E TCV were within specification.

3. Combustion overpressures during ignition for propellant and test article temperatures near 30°F ranged from 7 to 28 percent, with dual-bore and dry-bore starts tending to aggravate the overpressures.

4. Single circuit flight heater operation was found to heat the propellant lines and TCV at approximately 4 and 6°F/hr, respectively. Dual circuit operation raised the temperature of the propellant lines and TCV at the rates of 7 and 19°F/hr, respectively.

5. Ammonium nitrate salts, which developed on the downstream ball surfaces of the Mod I-D TCV as a result of high humidity air entering the injector, may have contributed to large (but within specification) leakage past the TCV balls during the posttest leakage checks.

6. The Mod I-D TCV propellant leakage rates all met the applicable specifications, but differential thermal contractions of the TCV actuator housings and pistons resulted in excessive leakage of the actuation GN_2 at low temperatures. The Mod I-D TCV operating times were erratic and failed to meet the specification for more than half of the firings.

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APPENDIXES

I. ILLUSTRATIONS
II. TABLES
III. TCV LEAKAGE CHECK PROCEDURES
IV. ENGINE PERFORMANCE

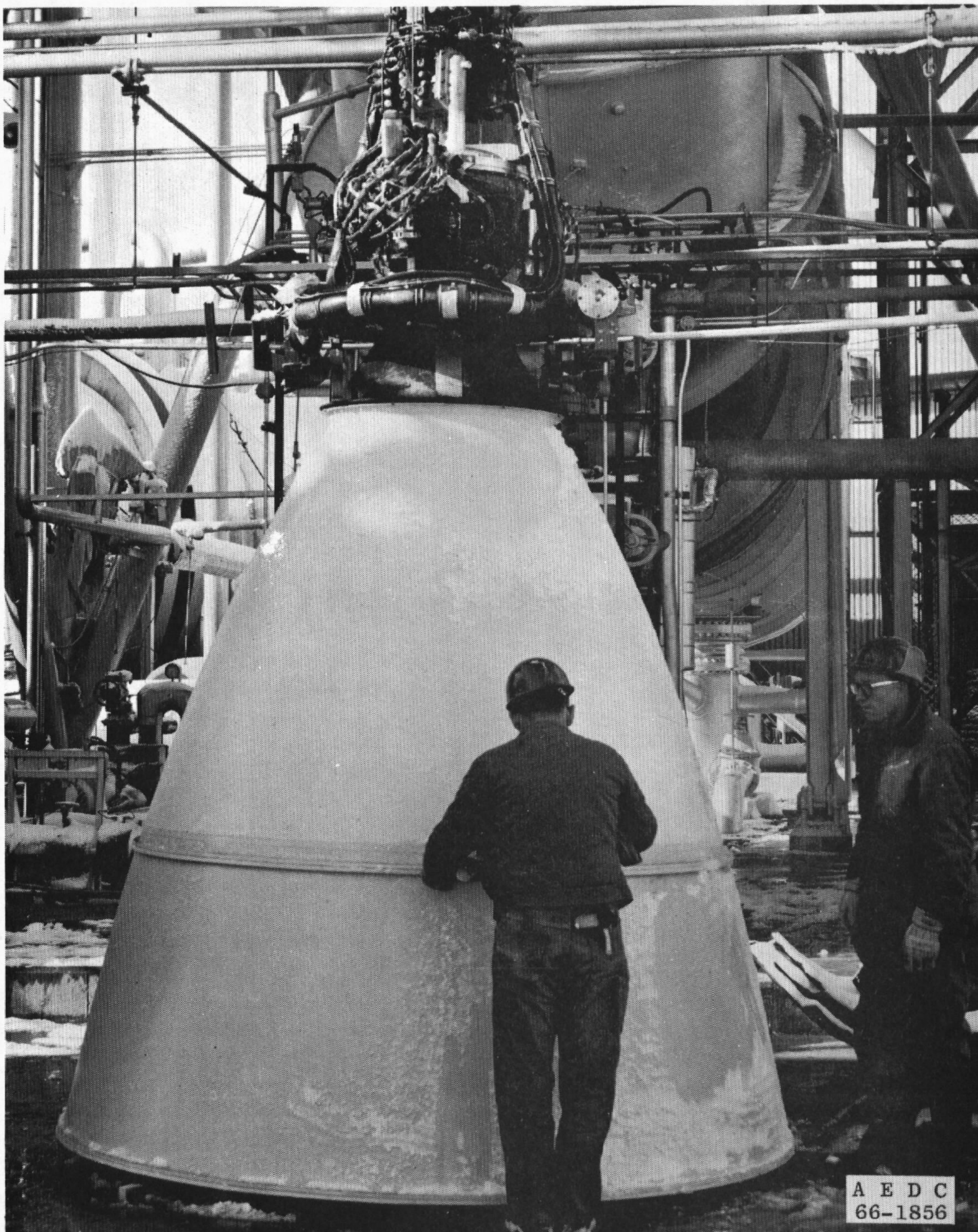
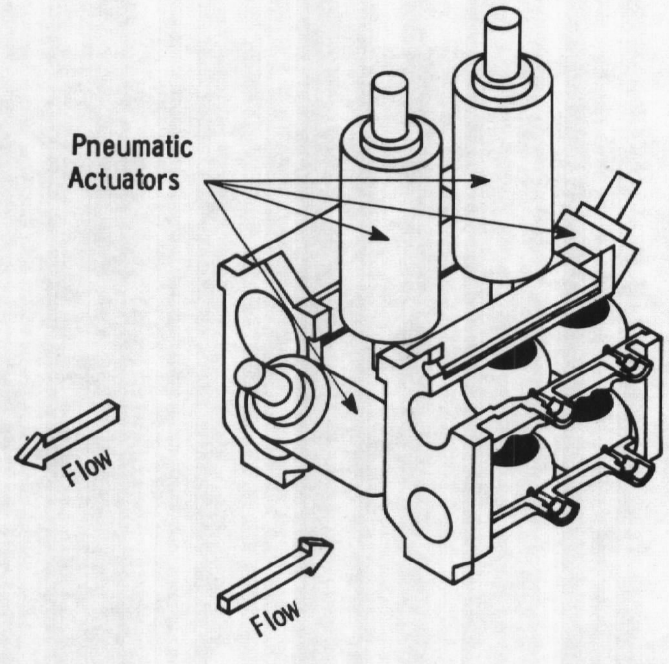
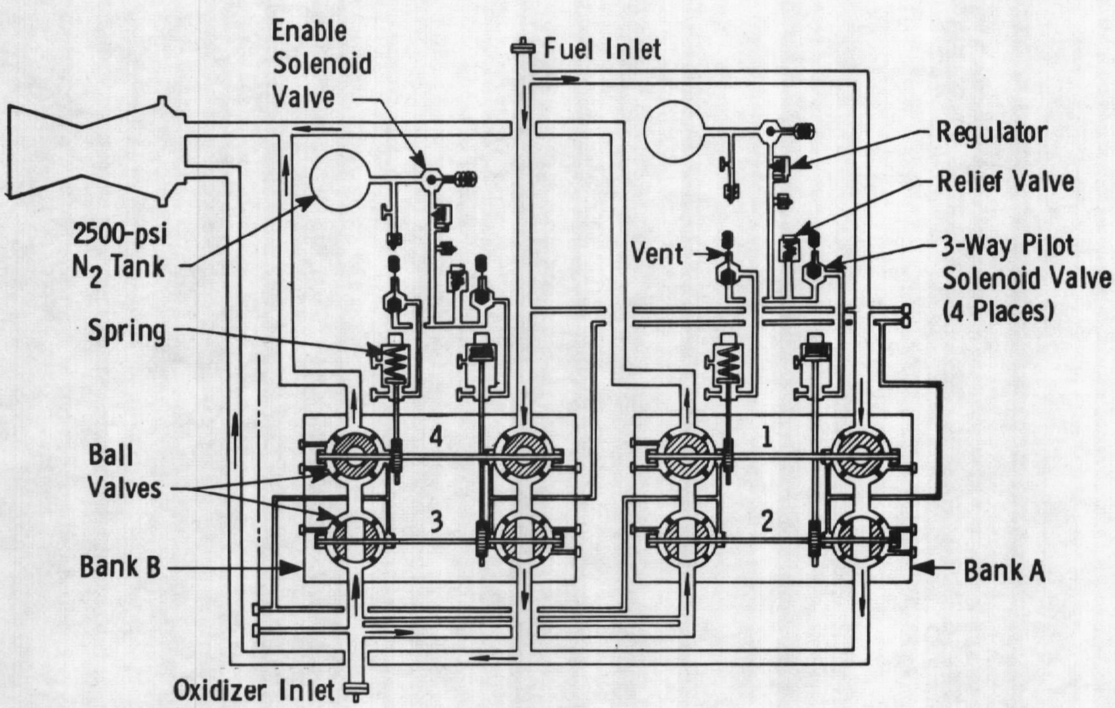


Fig. 1 The Apollo SPS Block II Engine



a. General Arrangement



b. Flow Diagram

Fig. 2 Block II TCV

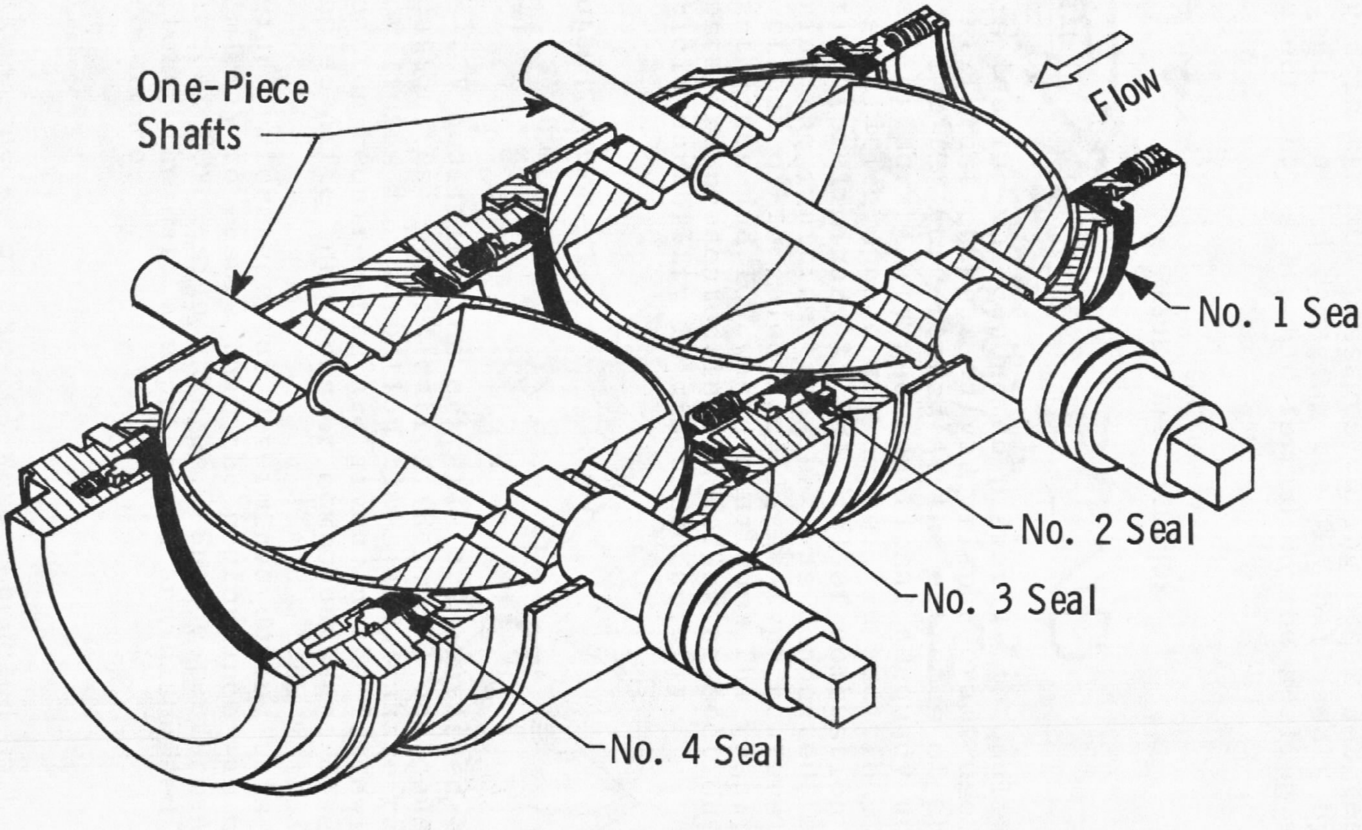


Fig. 3 TCV Ball and Seal Details

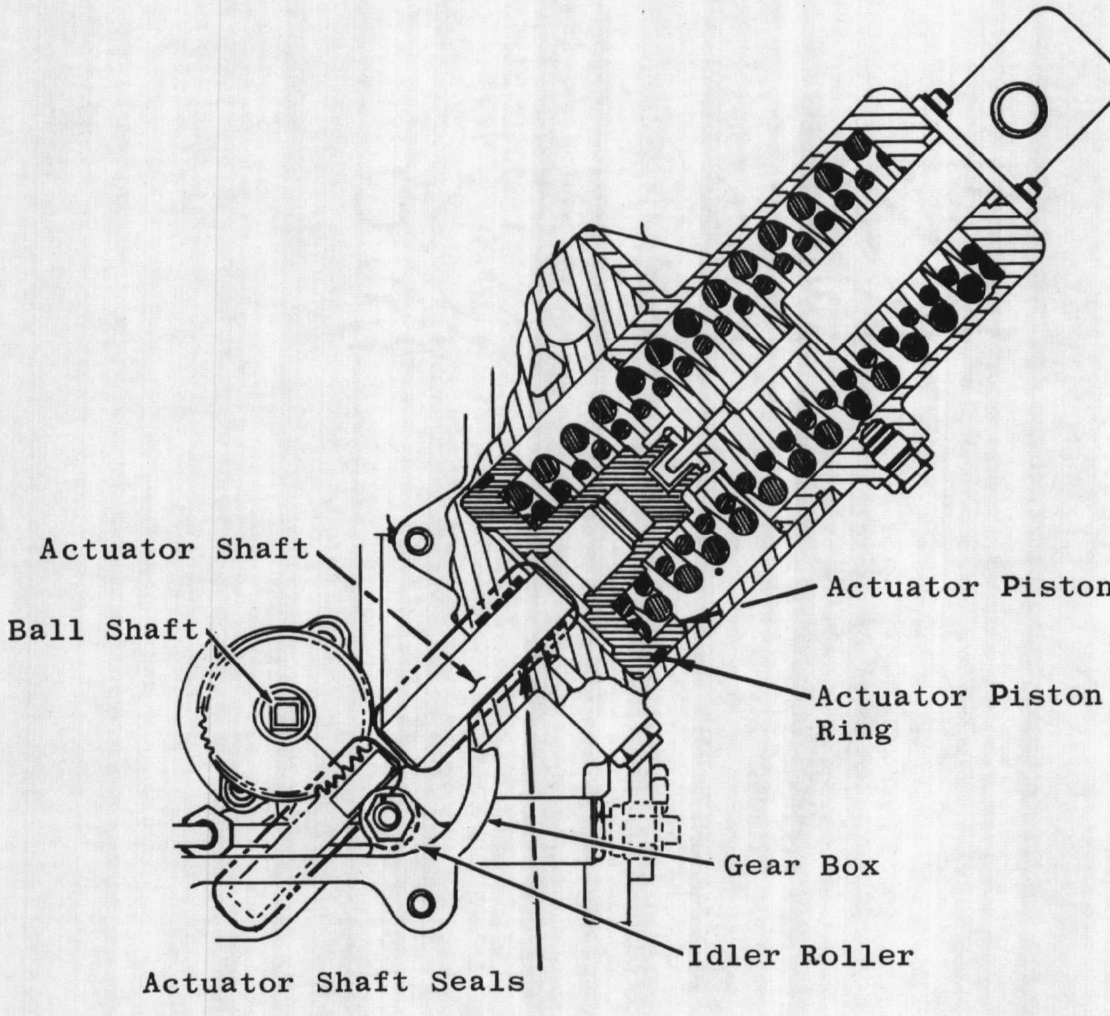
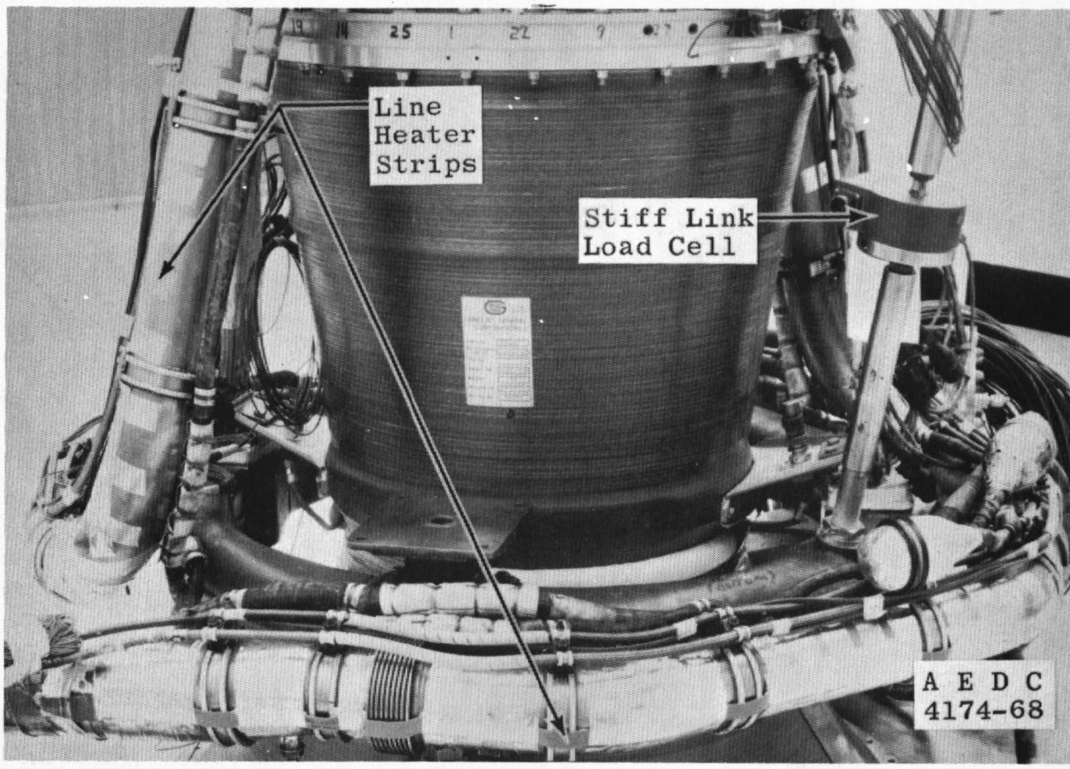
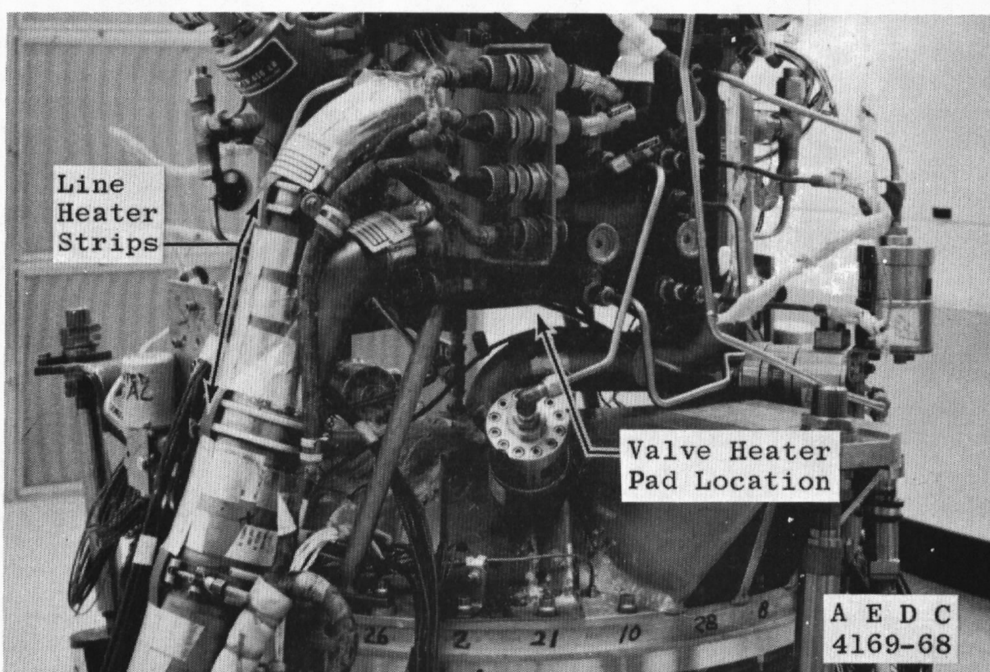


Fig. 4 The TCV Pneumatic Actuator

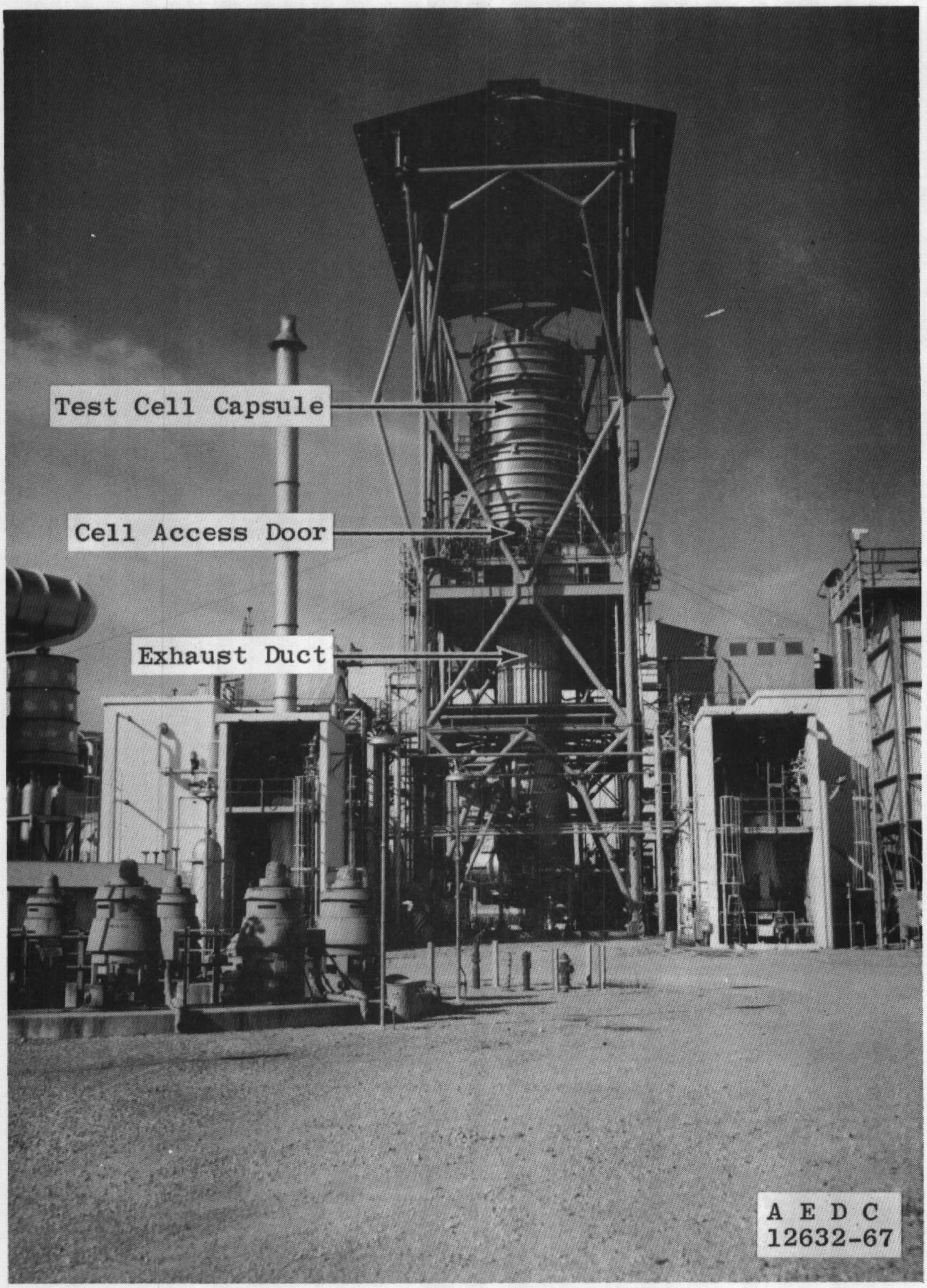


a. Propellant Lines



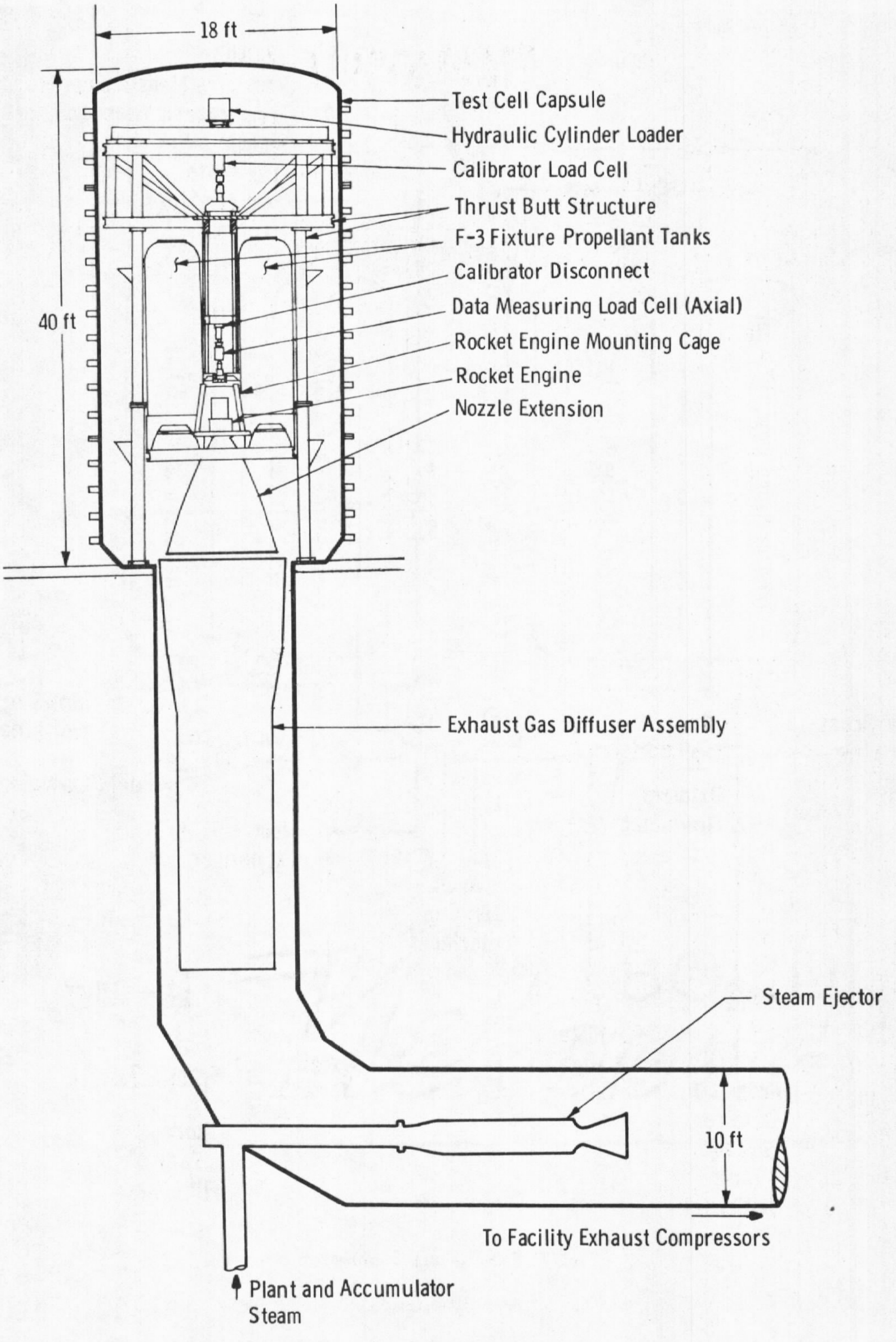
b. TCV

Fig. 5 Engine Electric Strip Heaters



a. Complex

Fig. 6 Propulsion Engine Test Cell (J-3)



b. Schematic

Fig. 6 Concluded

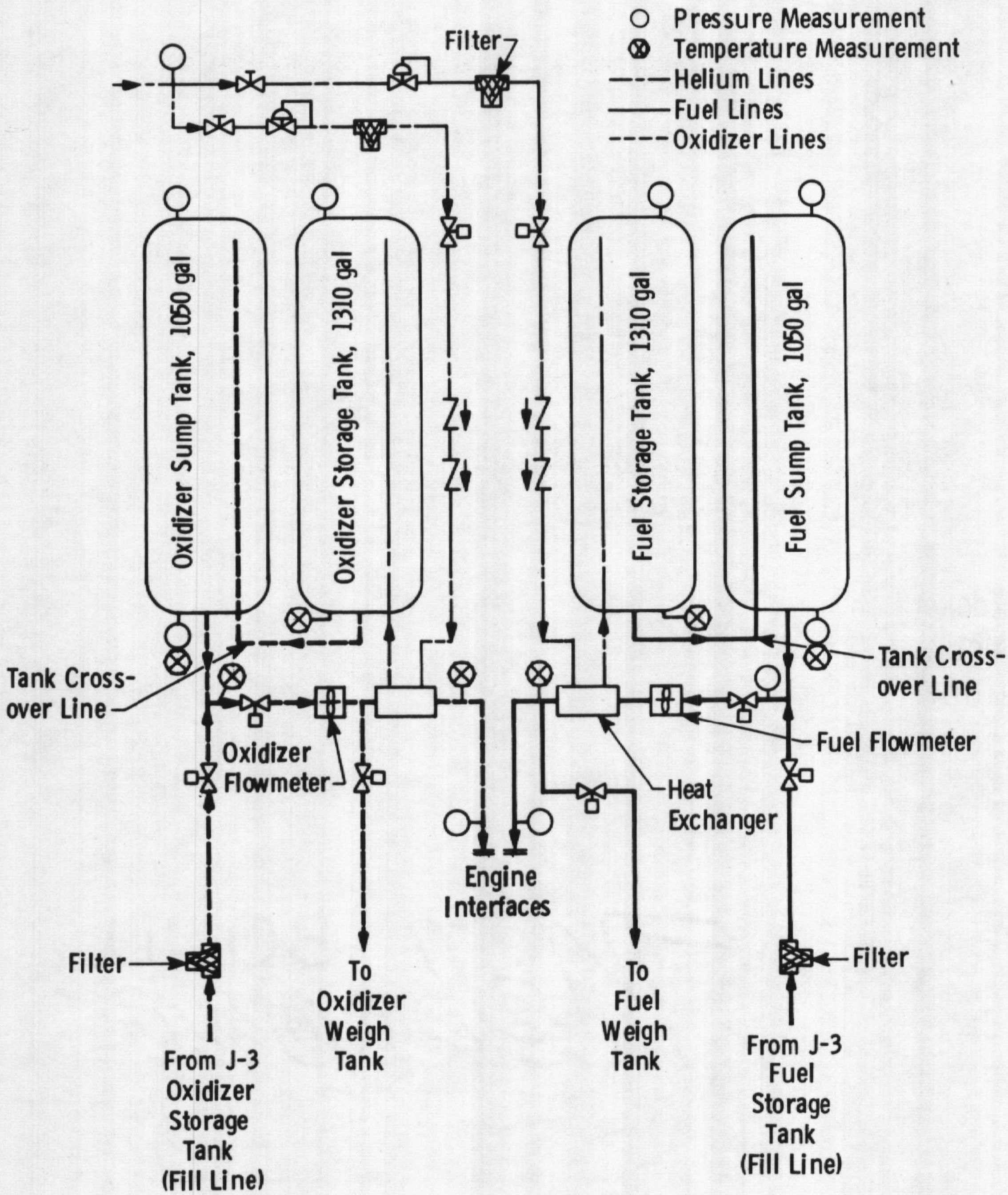


Fig. 7 F-3 Fixture Schematic

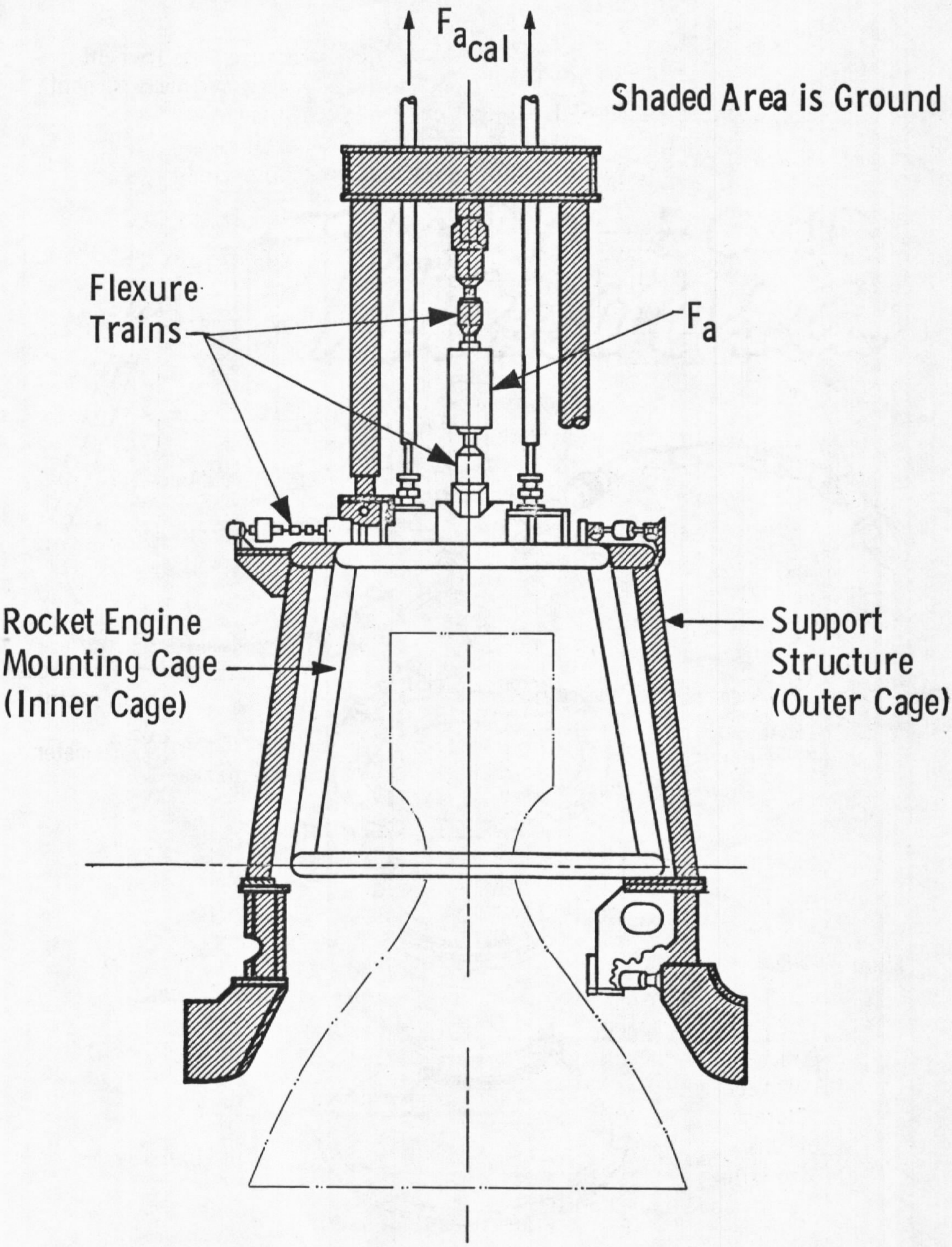


Fig. 8 Arrangement of Thrust System

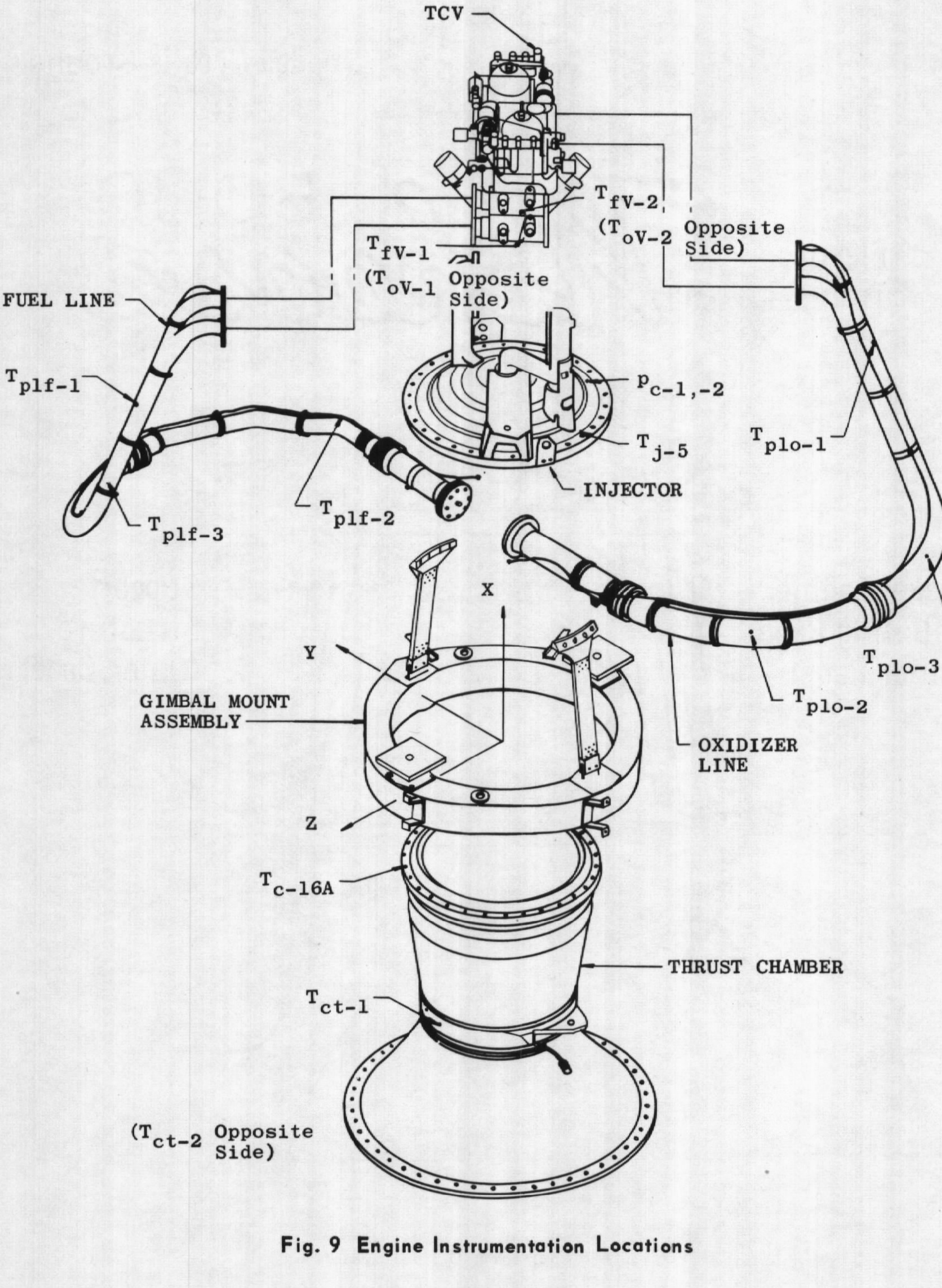
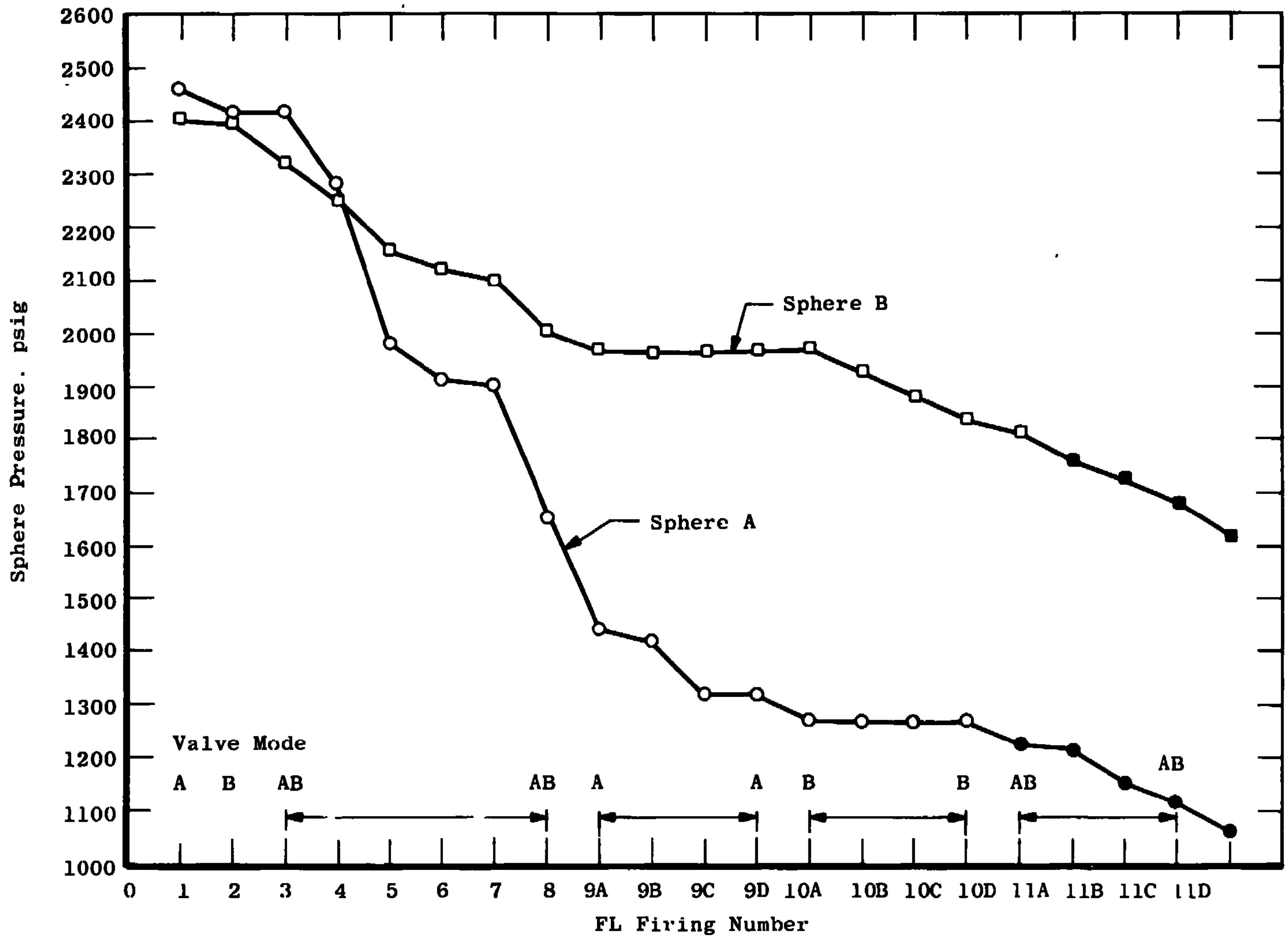
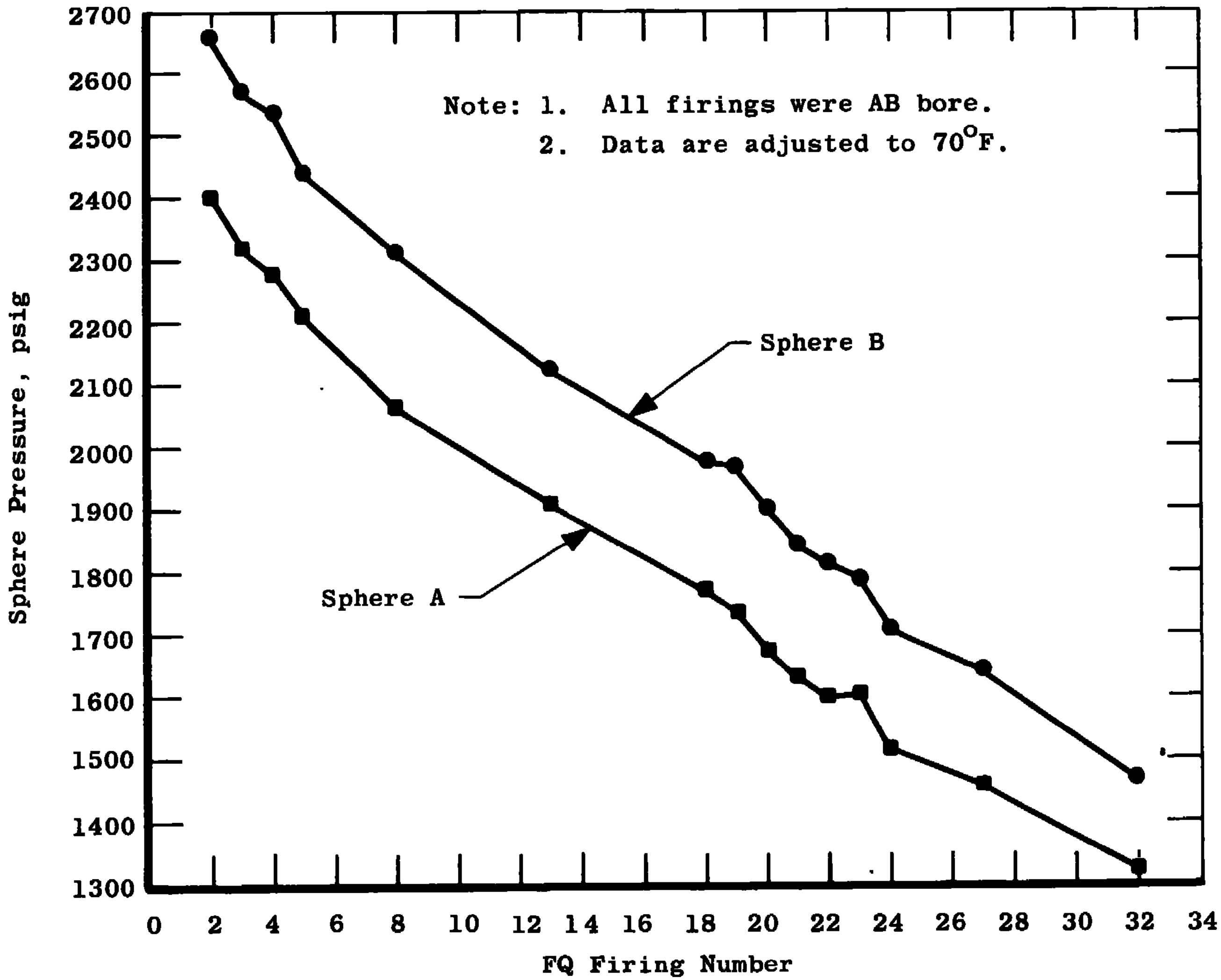


Fig. 9 Engine Instrumentation Locations



a. Mod I-D

Fig. 10 TCV Actuation Sphere Pressure History



b. Mod I-E

Fig. 10 Concluded

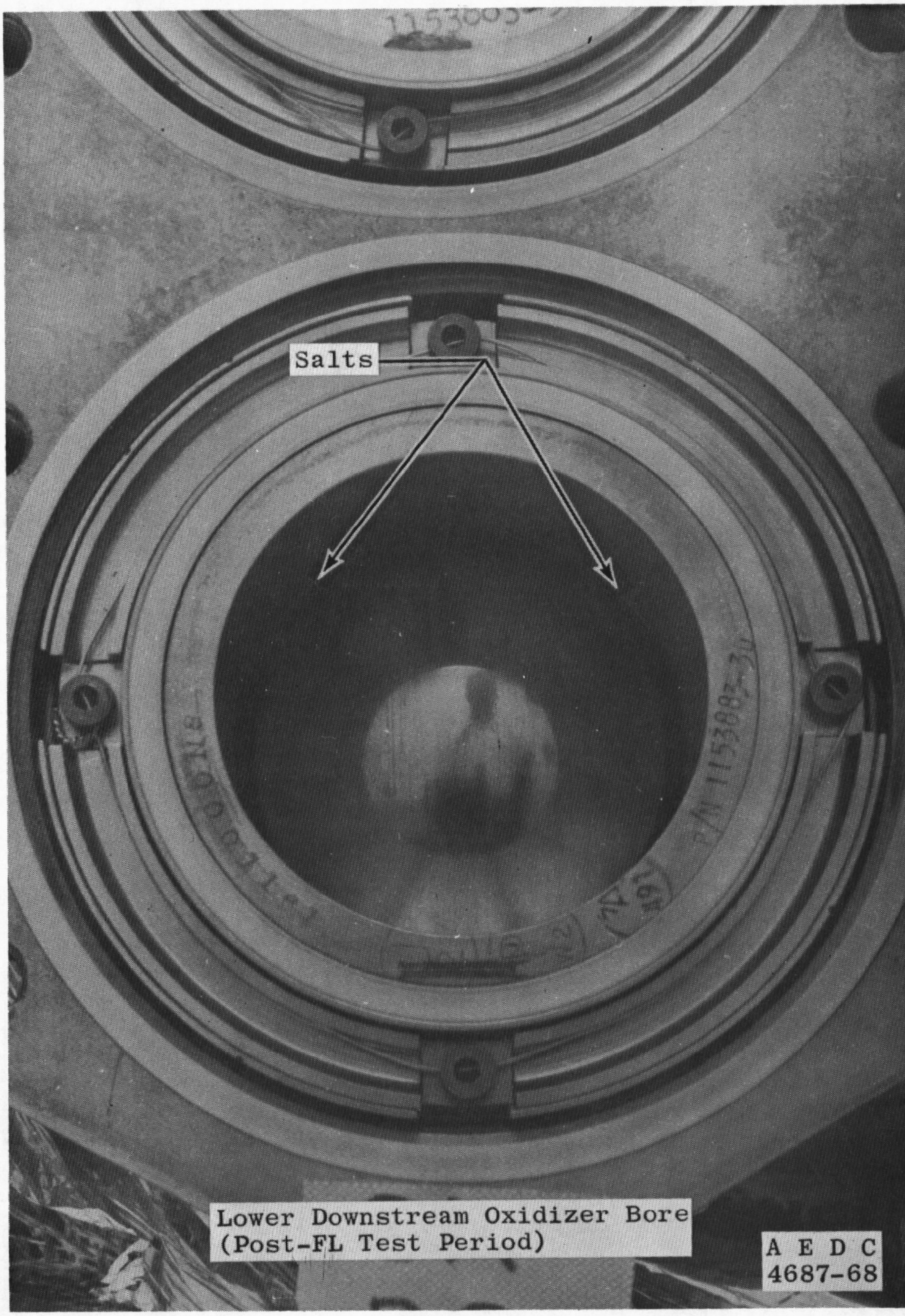


Fig. 11 Ammonium Nitrate Salt Formations

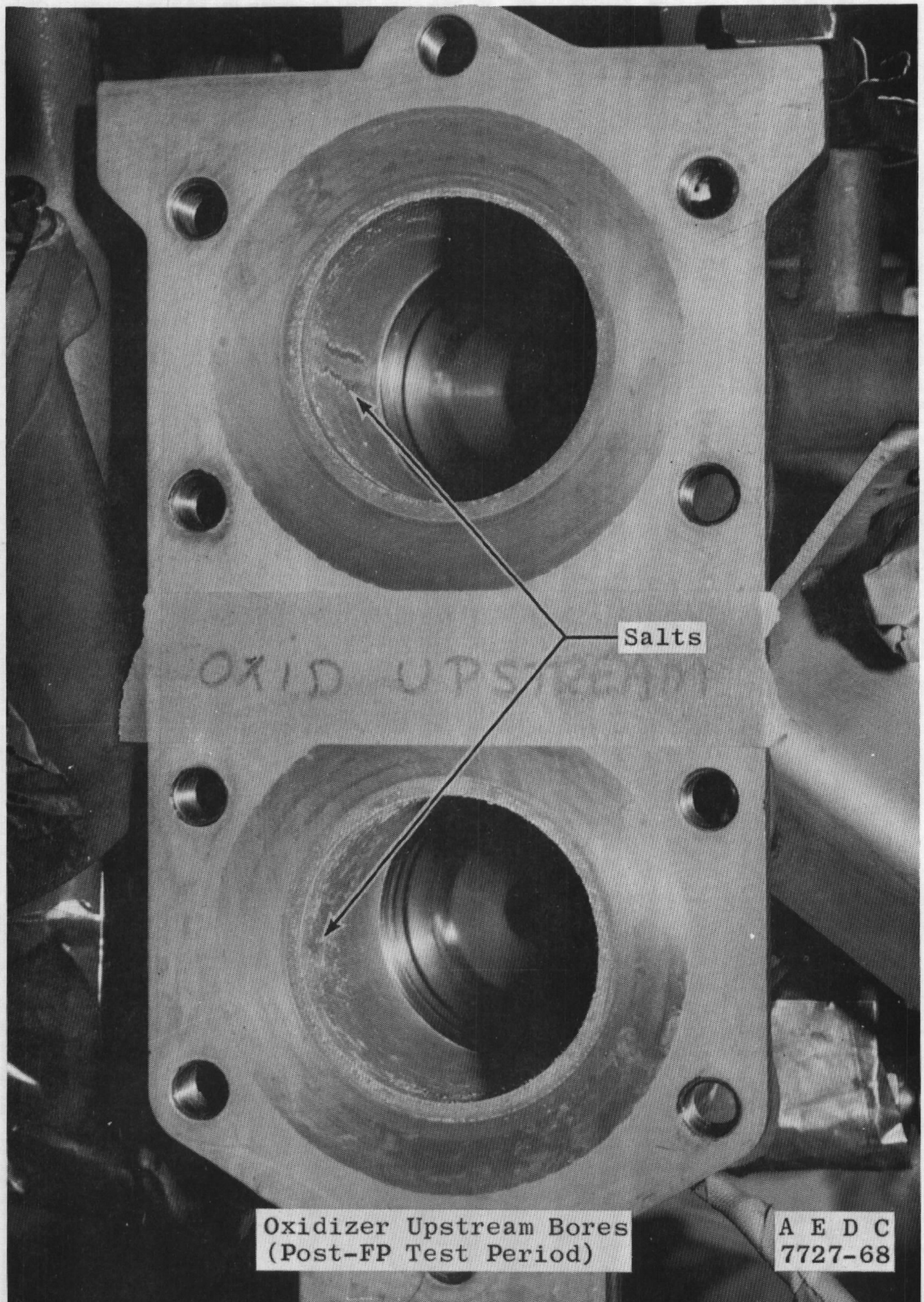
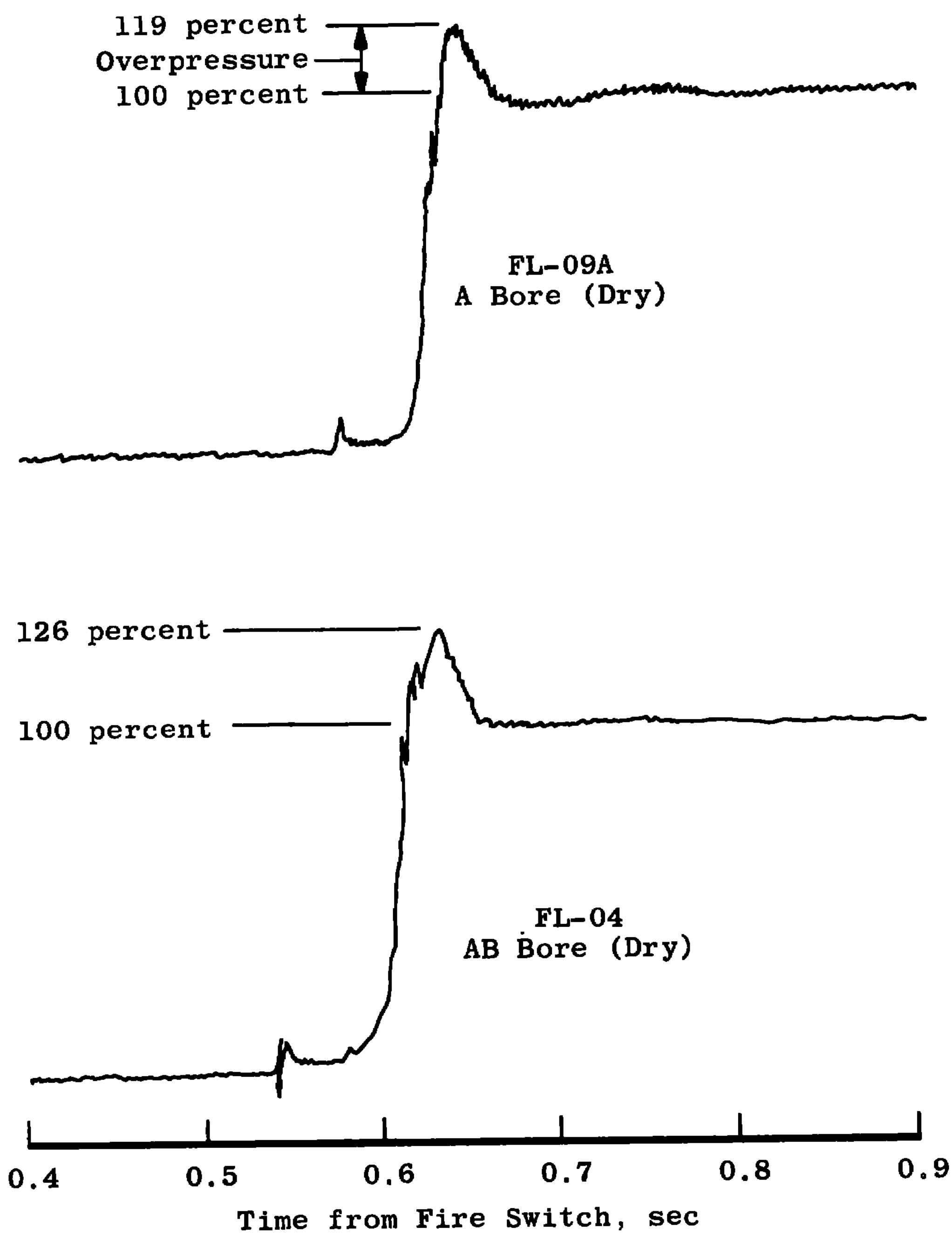
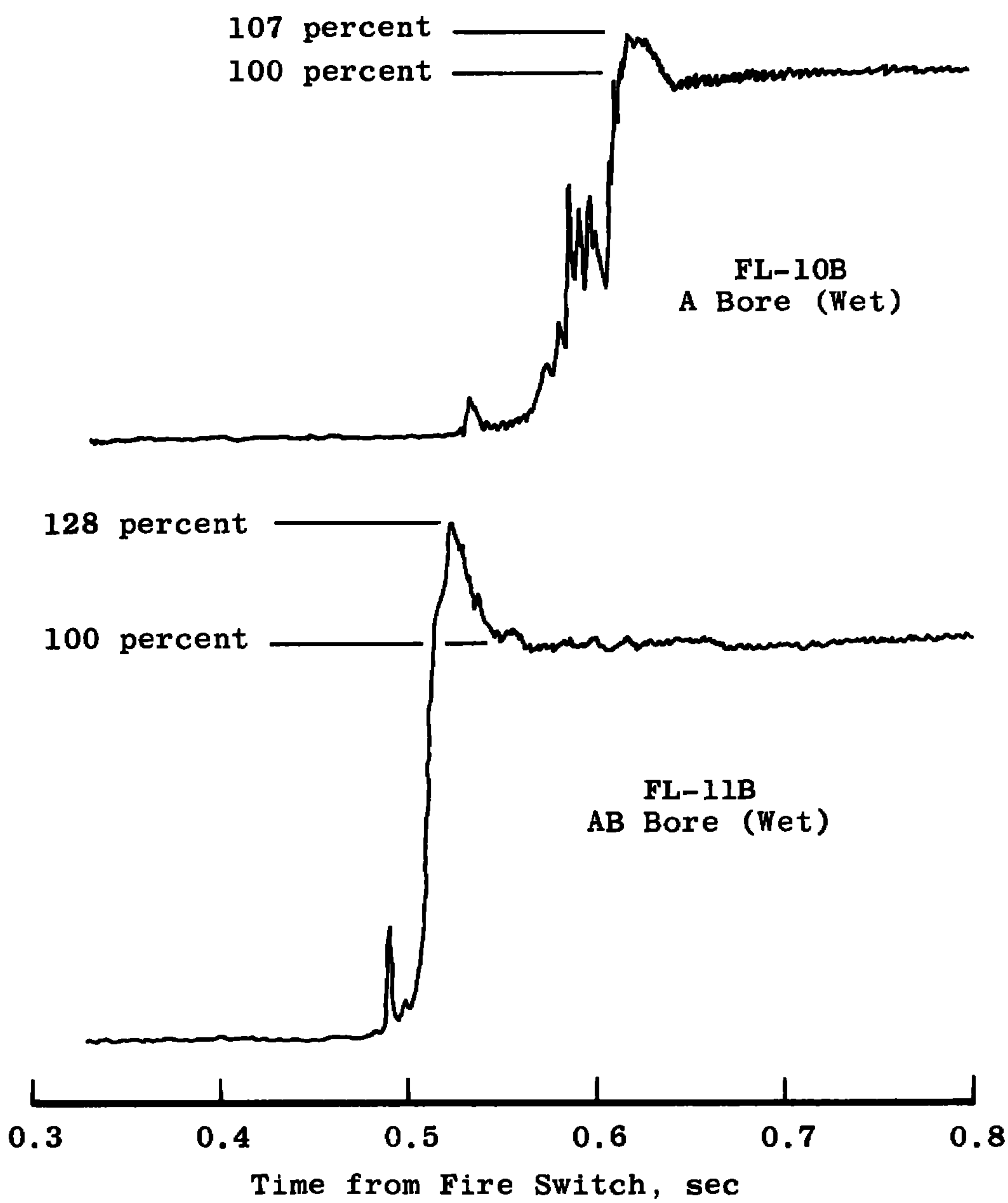


Fig. 12 Aluminum Nitrate Salt Formations



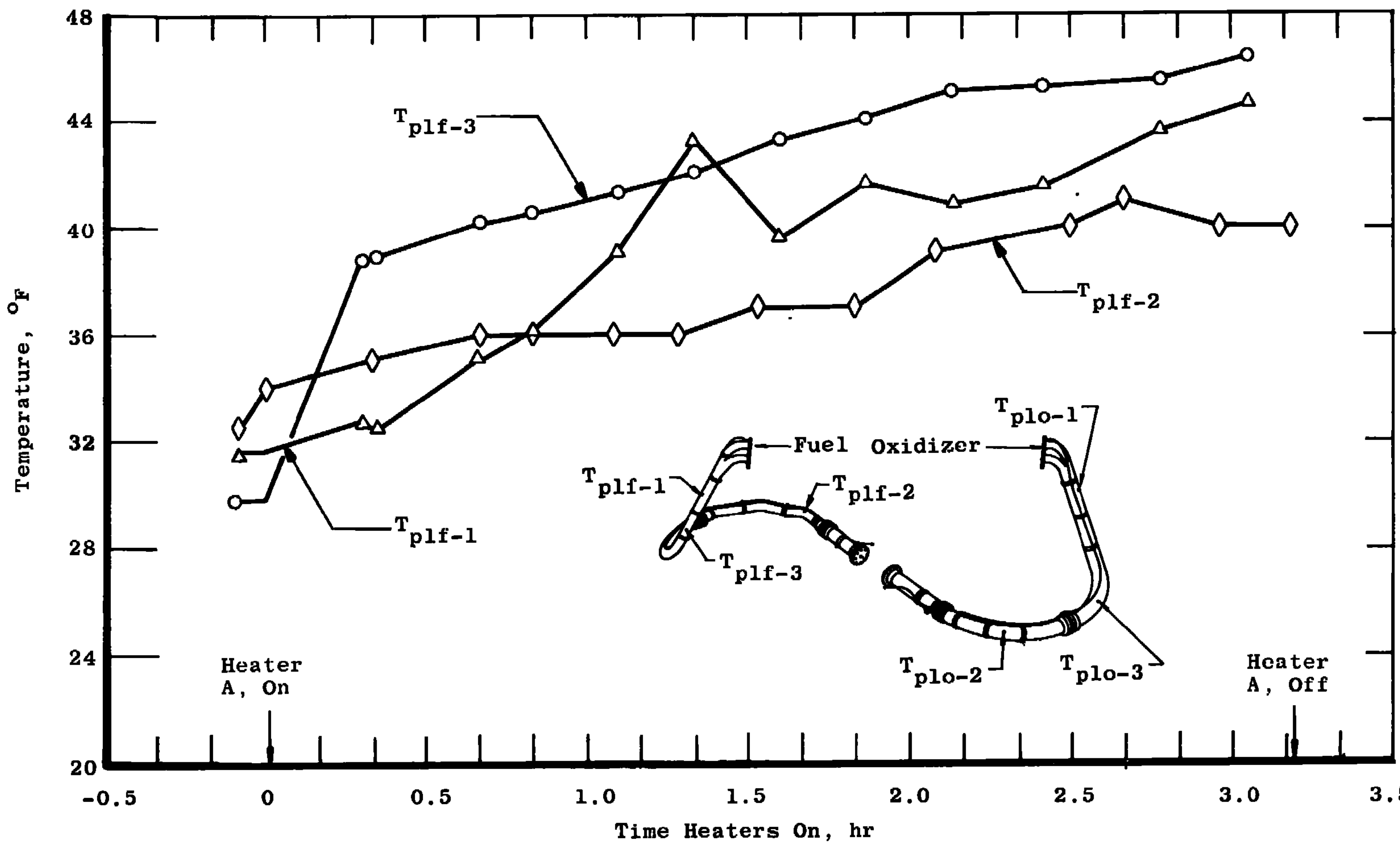
a. Dry Bore

Fig. 13 Combustion Overpressure History



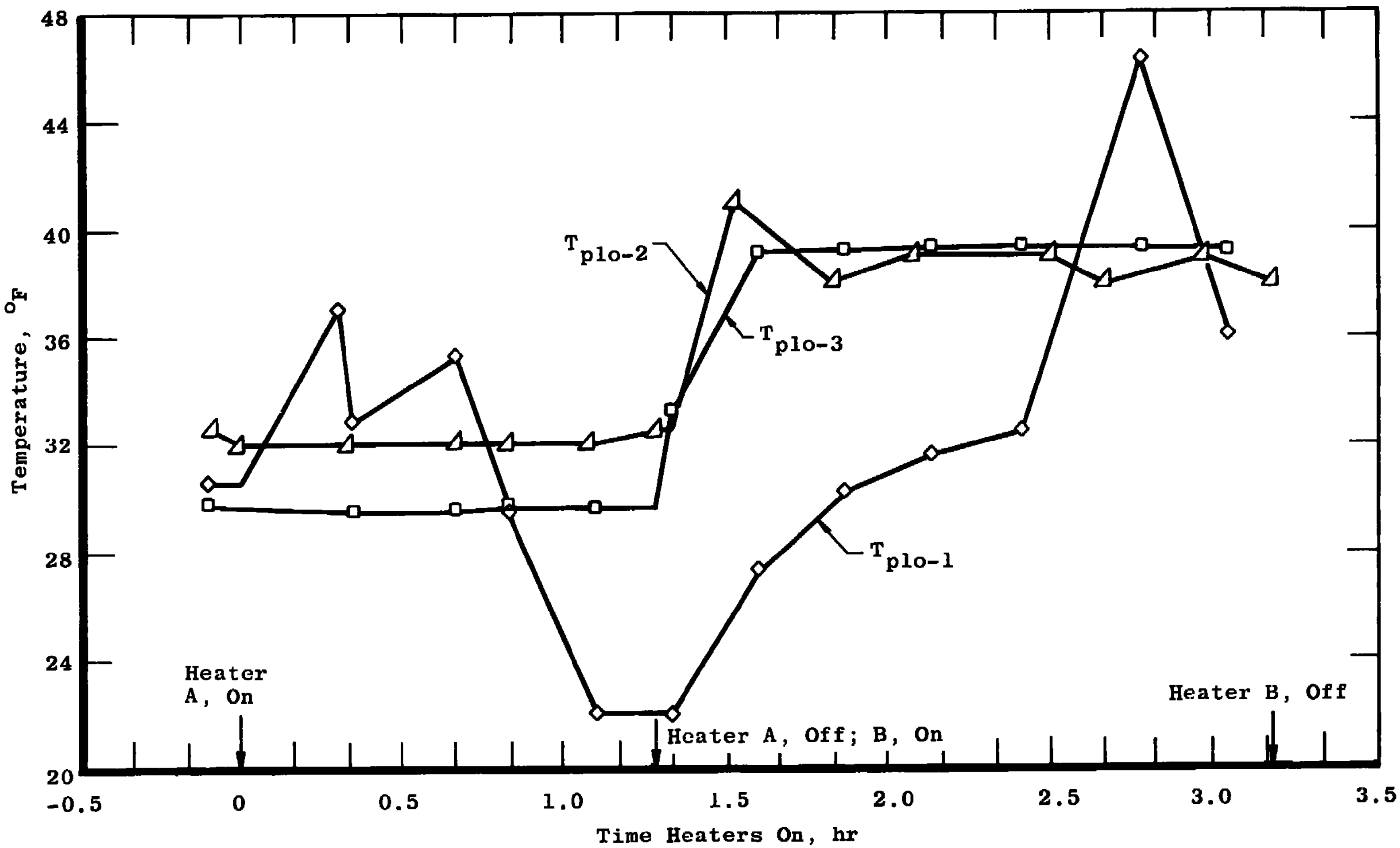
b. Wet Bore

Fig. 13 Concluded



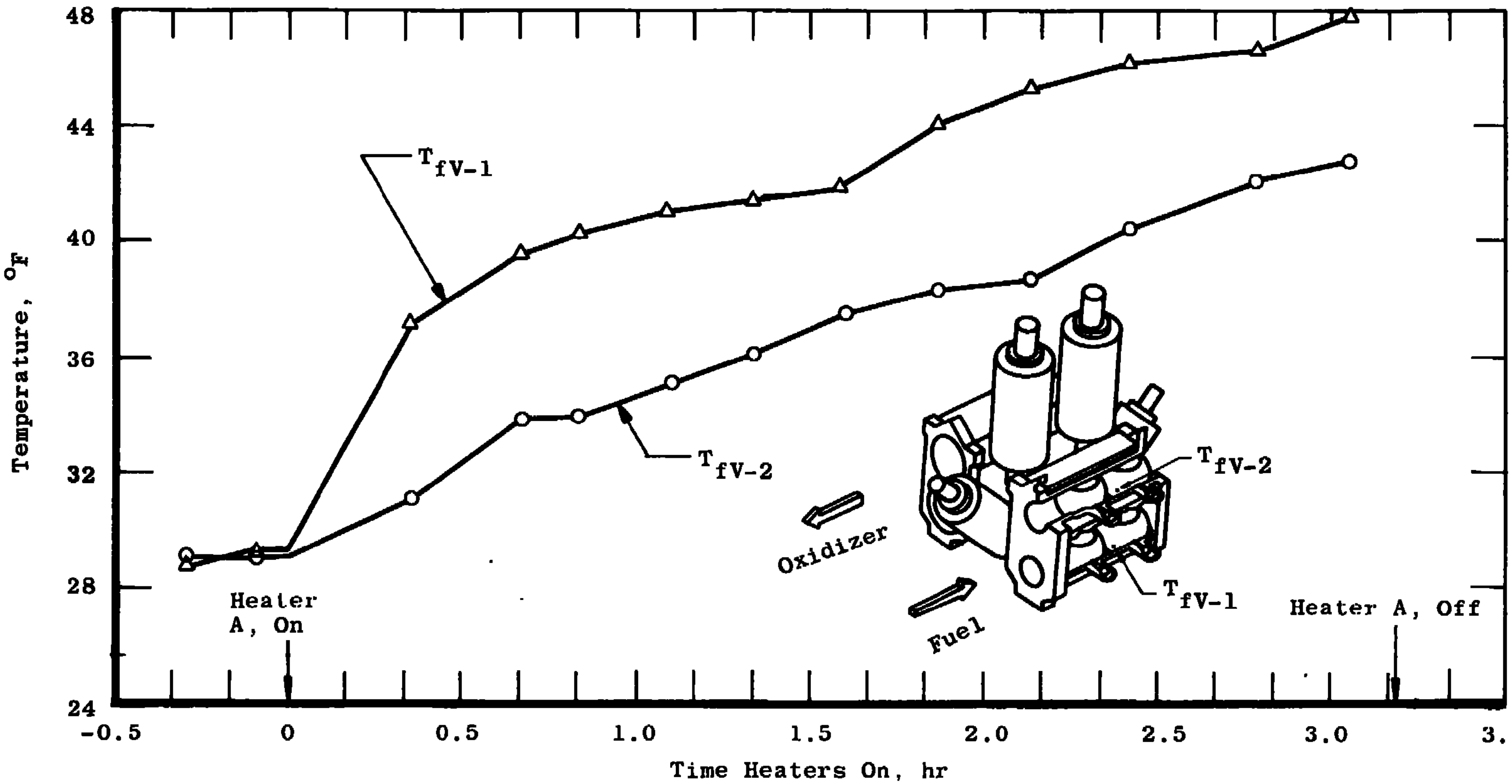
a. Fuel

Fig. 14 Propellant Line Temperature History, Single Heater Circuit



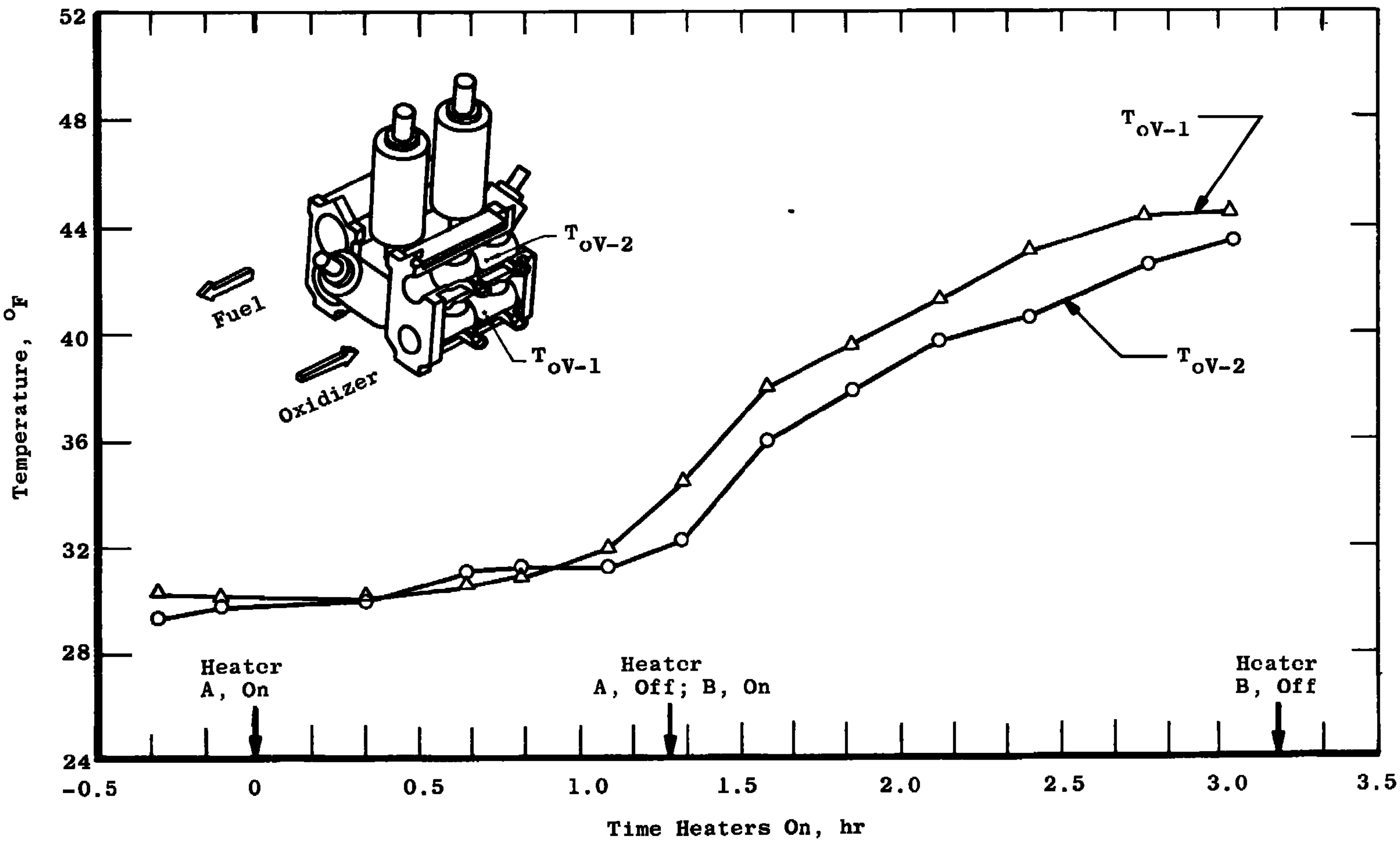
b. Oxidizer

Fig. 14 Concluded



a. Fuel Side

Fig. 15 TCV Temperature History, Single Heater Circuit



b. Oxidizer Size

Fig. 15 Concluded

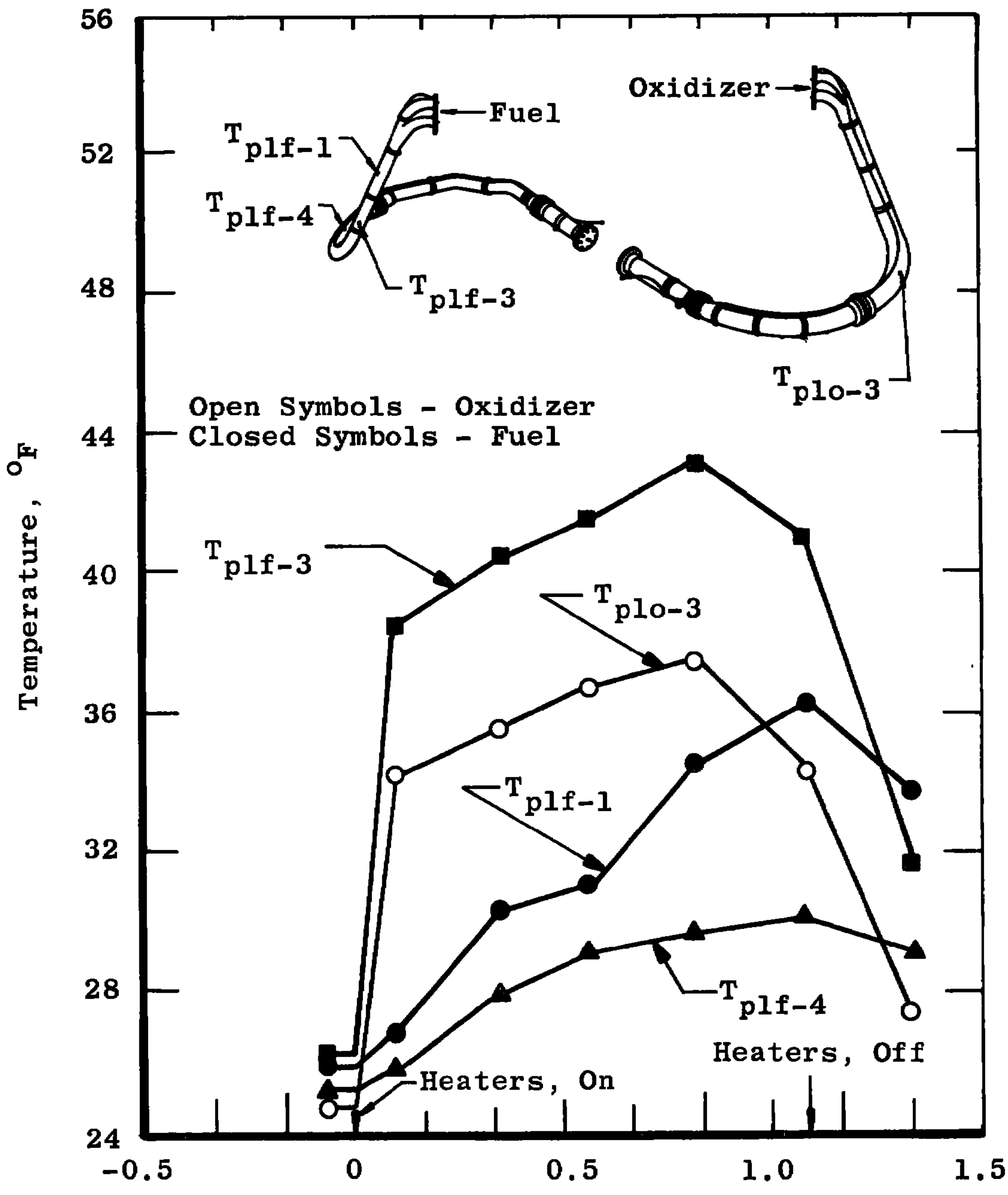


Fig. 16 Propellant Line Temperature History, Dual Heater Circuit

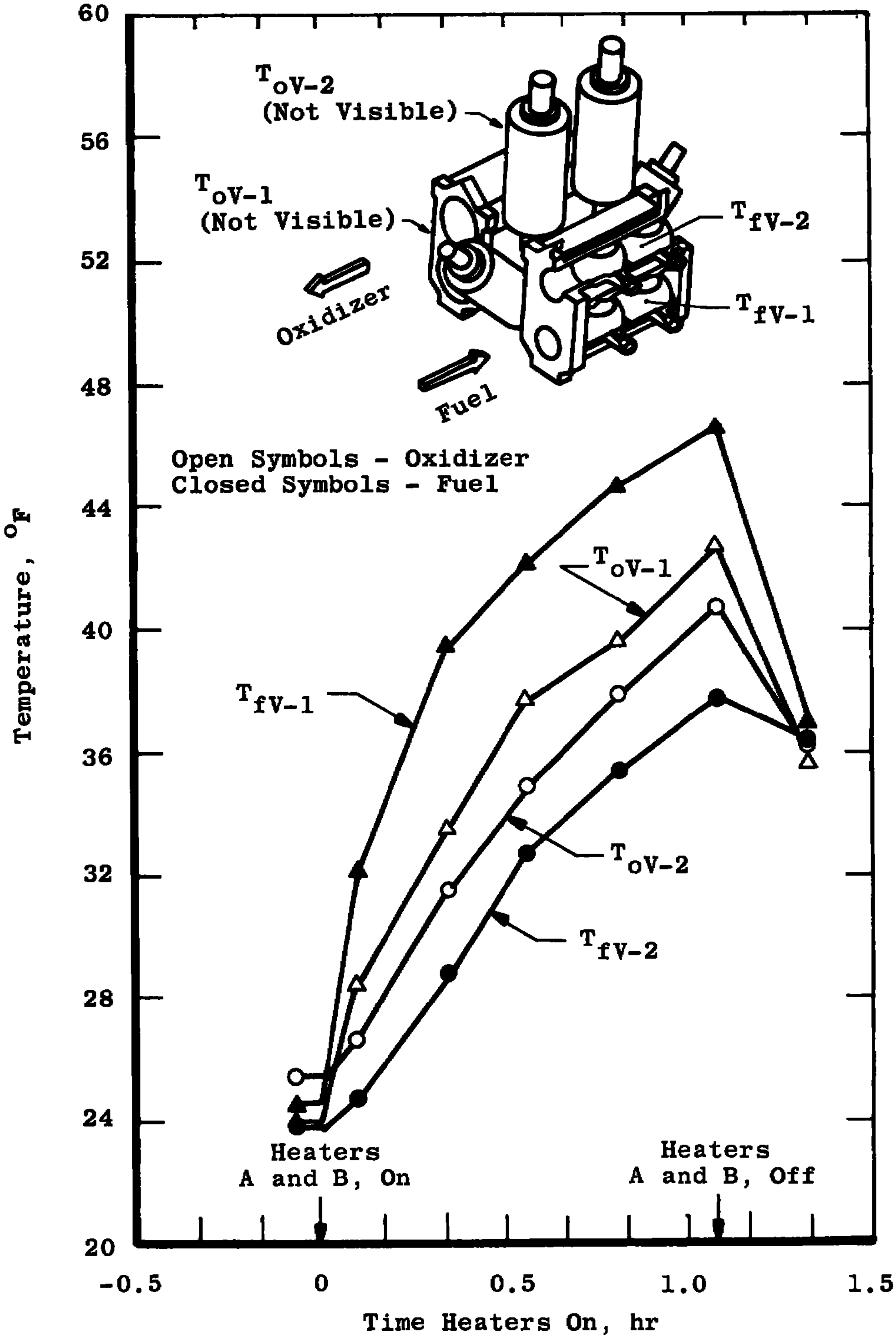


Fig. 17 TCV Temperature History, Dual Heater Circuit

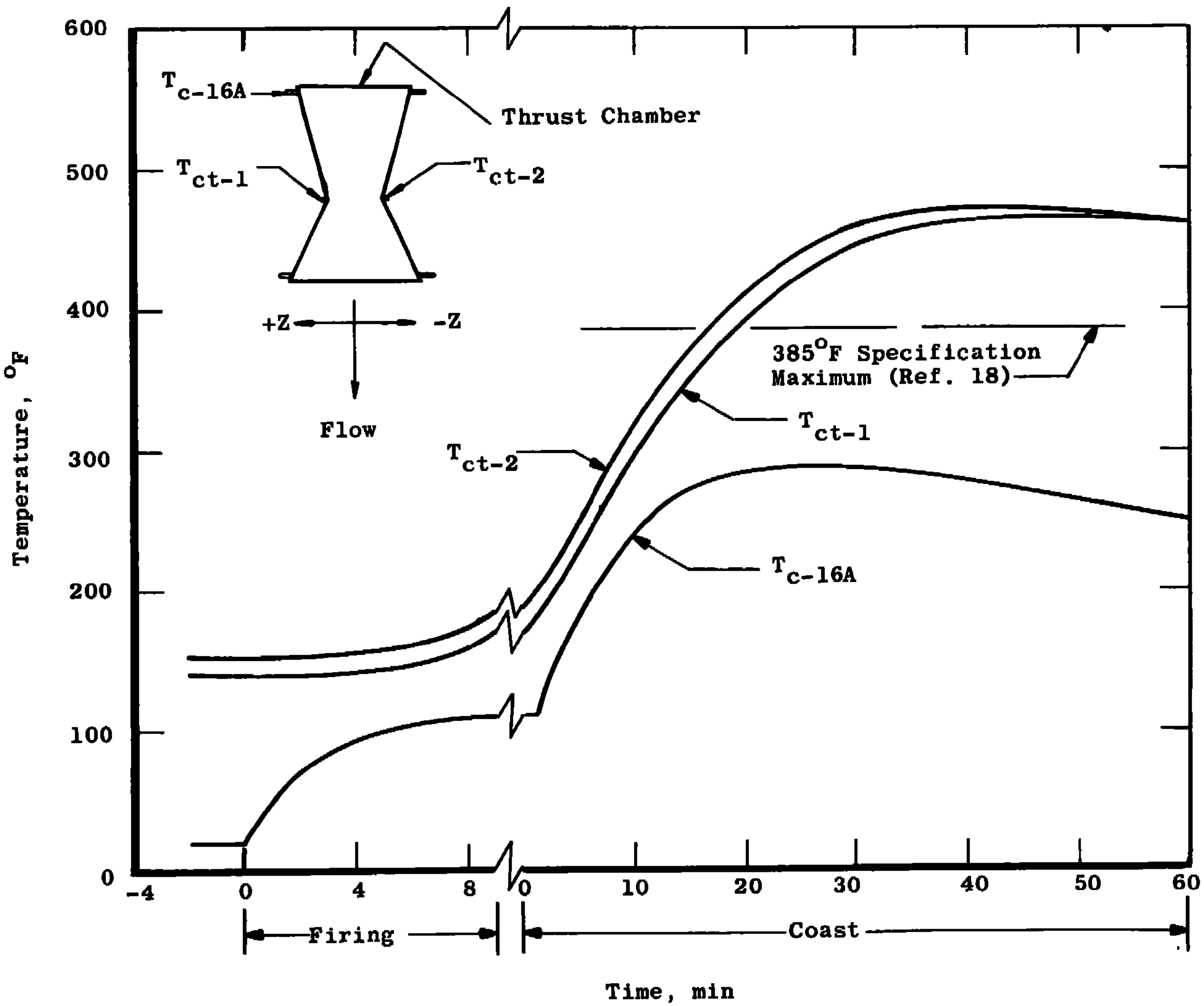


Fig. 18 Thrust Chamber Temperature History, 550-sec Firing (FQ-19)

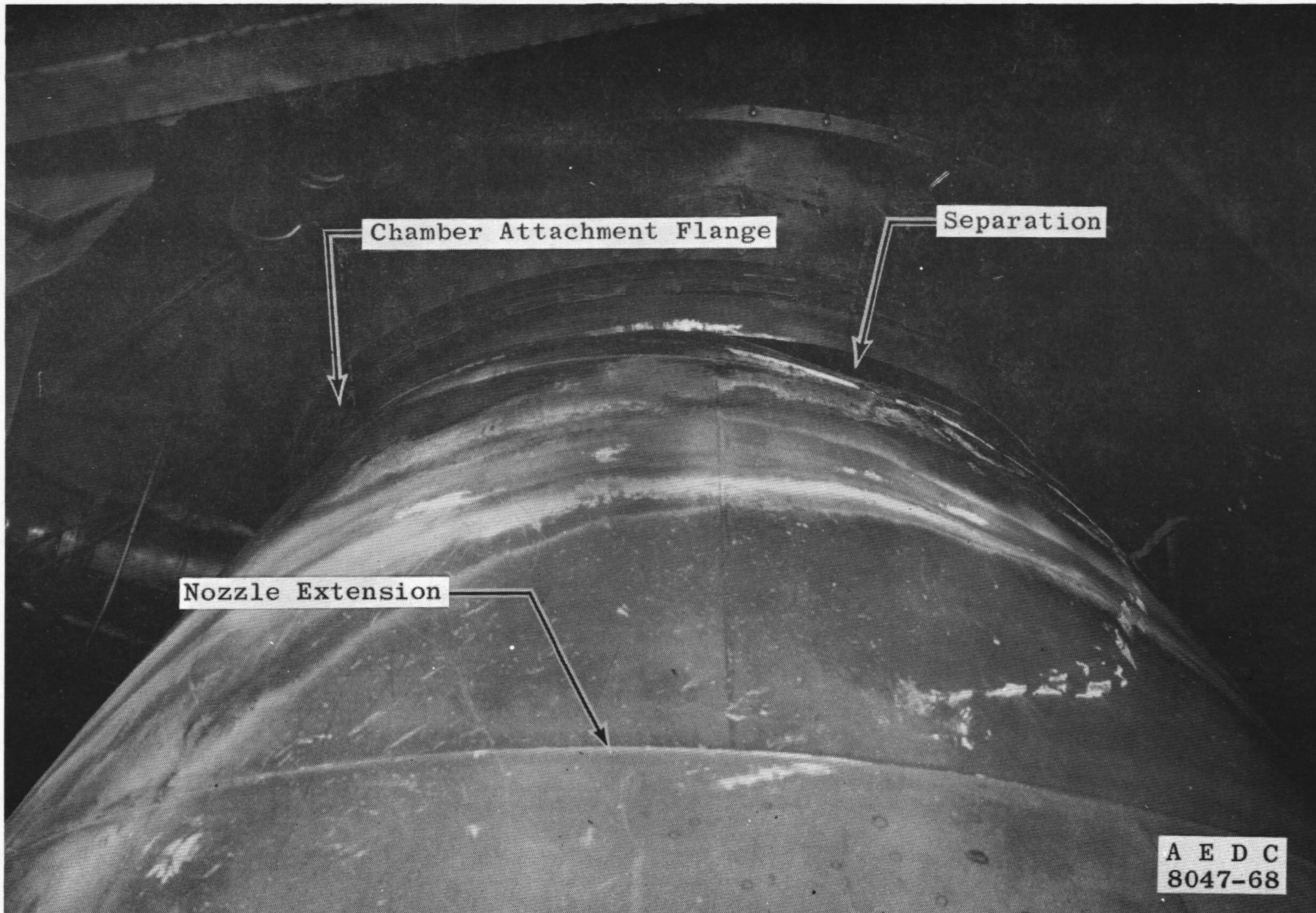


Fig. 19 Nozzle Extension Damage, Post-FQ Test Period

Fig. 20 Fuel Interface Screen Damage, Post-FL Test Period

TABLE I
TESTING SUMMARY

<u>Test Period FK</u> - Flight propellant line and TCV single-circuit heater checkout. Conducted on May 10, 1968. No engine firings.

<u>Test Period FL</u> - Flight propellant line and TCV dual-circuit heater checkout.

Firing No.	Nominal Firing Duration, sec	Coast Duration, min	Firing Time, CDT	TCV Bank Selected	Nominal Prefire Temp. Specified, °F		
					Propellants	T_{j-5}	T_{fV-1}
FL-01	8.7	-	2017	A	25 to 35	25 to 40	25 to 35
FL-02	7.6	190.0	2327	B			
-03	0.5	64.0	0031	AB			
-04	15.0	67.0	0138				
-05	57.0	66.0	0244				
-06	0.5	220.0	0624				
-07	20.0	18.0	0642				
-08	14.0	92.0	0814				
-09A	1.0	127.0	1021	A			
-09B		1.0	1022				
-09C		1.0	1023				
-09D		1.0	1024				
-10A		30.0	1054	B			
-10B		1.0	1055				
-10C		1.0	1056				
-10D		1.0	1057				
-11A		29.0	1126	AB			
-11B		1.0	1127				
-11C		1.0	1128				
-11D		1.0	1129				

Test period FL was conducted on May 14 and 15, 1968. Total accumulated firing time was 139.25 sec. Target thrust chamber pressure for all firings was 100 psia. Target mixture ratio for all firings was 1.60.

Test periods FM, FN, and FO are reported in Ref. 15.

TABLE I (Concluded)

Test Period FP -

Firing No.	Nominal Firing Duration, sec	Firing Time, CDT	TCV Bank Selected	Nominal Prefire Temp. Specified, °F		
				Propellants	T_{oV-1}	T_{fV-1}
FP-01	30	0111	A, AB, B (10 sec each)	30 to 35	30 to 35	30 to 35

Test period FP was conducted on August 7, 1968, and was discontinued because of high mixture ratio operation. The engine was re-orificed prior to test period FQ. Target chamber pressure was 100 psia.

Test Period FQ -

Firing No.	Nominal Firing Duration, sec	Coast Duration, min	Firing Time, CDT	Chamber Pressure, psia	Nominal Prefire Temp. Specified, °F		
					Propellants	T_{oV-1}	T_{fV-1}
FQ-02	30.0	-	0950	100	30-35	30-35	30-35
-03	1.0	89.0	1119	110			
-04	1.0	20.0	1139				
-05	1.0	41.0	1220				
-06	1.0	1.0	1221				
-07	1.0	1.0	1222				
-08	0.6	22.0	1244				
-09	0.6	0.5	1244				
-10	0.6	0.5	1245				
-11	0.6	0.5	1245				
-12	0.6	0.5	1246				
-13	0.4	25.0	1311				
-14	0.4	0.5	1311				
-15	0.4	0.5	1312				
-16	0.4	0.5	1312				
-17	0.4	0.5	1313				
-18	10.0	19.0	1332				
-19	550.0	287.0	1819				
-20	10.0	205.0	2244		110-115	None	None
-21	10.0	109.0	0033				
-22	10.0	32.0	0105				
-23	100.0	30.0	0135	100			
-24	5.0	156.0	0411	117			
-25	5.0	1.0	0412				
-26	5.0	1.0	0413				
-27	1.0	30.0	0443				
-28	1.0	1.0	0444				
-29	1.0	1.0	0445				
-30	1.0	1.0	0446				
-31	1.0	1.0	0447				

Test period FQ was conducted on August 22 and 23, 1968. Total accumulated firing time was 752.49 sec. Target mixture ratio for all firings was 1.60. All firings except FQ-02 were selected for dual-bore TCV operation. Firing FQ-02 TCV operation was A, AB, B for 10 sec each.

TABLE II
TCV LEAKAGE RATES WITH GN_2
a. Mod I-D (S/N 122)

Ball Seals	Specification Leakage Limit (Ref. 18), cc/hr	Pre-FL Leakage, cc/hr — Differential Pressure, psi: 2 to 5	100 to 105	200 to 205	2 to 5	Post-FL Leakage, cc/hr — Differential Pressure, psi: 2 to 5	100 to 105	200 to 205	2 to 5
Upper Fuel Bore	Prefire - For the two seals on each ball, one may leak up to 300 cc/hr and the other up to 5000 cc/hr. Postfire - For the two seals on each ball, one may leak up to 400 cc/hr and the other up to 10,000 cc/hr.								
1		0	0	0	0	0	342	600	0
2		0	15	10	5	0	0	0	0
3		0	0	0	0	0	0	0	0
4		0	7.5	4.0	0	0	0	0	0
Lower Fuel Bore									
1		0	0	4.0	0	0	600	389	0
2		0	0	0	0	0	0	0	0
3		0	5.0	0	0	0	0	0	0
4		0	0	0	0	0	0	0	0
Upper Oxidizer Bore									
1		0	0	2.0	0	5	45	10	25
2		0	5.0	10.0	0	25	200	600	80
3		0	0	0	0	0	62.5	212	0
4		0	5.0	2.5	0	0	50	42.5	2.5
Lower Oxidizer Bore									
1		11.0	30.0	5.0	5.0	5	243	330	0
2		0	0	0	0	5	130	130	15
3		0	5.0	5.0	0	0	3	2.5	0
4		0	0	0	0	12.5	5148	9000	21.5
Shaft Seals (Valve Closed)									
Fuel - 1 and 4	20	0	0	0	0	0	0	0	0
2 and 3	40	0	0	0	0	0	0	0	0
Oxidizer -									
1 and 4	40	0	0	0	0	0	0	2.5	0
2 and 3	20	0	0	0	0	0	0	5.0	0
(Valve Open)			(10 psig)				(70 ± 2 psig)		
Fuel - All	40	0	0	-	0	0	0	-	0
Oxidizer - All	40	0	0	-	0	0	0	-	0

TABLE II (Concluded)

b. Mod I-E (S/N 126)

Ball Seals	Specification Leakage Limit (Ref. 18), cc/hr	Pre-FP Leakage, cc/hr — Differential Pressure, psi: 2 to 5	100 to 105	200 to 205	2 to 5	Post-FQ Leakage, cc/hr — Differential Pressure, psi: 2 to 5	100 to 105	200 to 205	2 to 5
Upper Fuel Bore	Prefire - For the two seals on each ball, one may leak up to 300 cc/hr and the other up to 5000 cc/hr. Postfire - For the two seals on each ball, one may leak up to 400 cc/hr and the other up to 10,000 cc/hr.								
1		0	0	0	0	4	8	5	1
2		0	0	0	0	9	263	450	9
3		0	0	0	0	0	18	8	0
4		0	0	0	0	0	1	3	0
Lower Fuel Bore									
1		8	5	2	1	0	11	23	0
2		0	0	0	0	10	368	960	10
3		6	23	15	8	5	45	44	5
4		0	0	5	0	0	9	14	0
Upper Oxidizer Bore									
1		3	5	0	0	11	400	1390	134
2		0	20	35	1	0	0	0	0
3		2	23	35	1	1500	26,400	48,900	1320
4		0	25	41	0	0	0	0	0
Lower Oxidizer Bore									
1		0	0	0	0	100	2400	2250	93
2		0	26	50	0	9	16	49	4
3		0	0	0	0	3	5	1	5
4		0	20	25	0	42	720	1680	25
Shaft Seals (Valve Closed)									
Fuel - 1 and 4	20	0	0	0	0	0	0	0	0
2 and 3	40	0	0	0	0	0	0	0	0
Oxidizer -									
1 and 4	40	0	0	0	0	0	0	0	0
2 and 3	20	0	0	0	0	0	0	0	0
(Valve Open)									
Fuel - All	40	0	0	0	0	0	0	0	0
Oxidizer - All	40	0	0	8	3	0	0	5	0

TABLE III
TCV ACTUATOR GN_2 LEAKAGE

	Actuator Piston Seal Leakage, cc/hr		Actuator Piston Shaft Seal Leakage, cc/hr	
	Mod I-D (S/N 122)	Mod I-E (S/N 126)	Mod I-D	Mod I-E
	Cold (≈ 20°F)	Ambient (≈ 20°F)	Cold (≈ 20°F)	Ambient (≈ 70°F)
LOWER BORE ("A")				
Actuator No. 1				
50-percent Open	24,600	14	0	0
75-percent Open	18,700	-	0	-
100-percent Open	0	0	0	0
Actuator No. 2				
50-percent Open	0	0	0	0
75-percent Open	0	-	0	-
100-percent Open	0	0	0	0
UPPER BORE ("B")				
Actuator No. 3				
50-percent Open	0	185	9,780	0
75-percent Open	0	-	11,640	-
100-percent Open	0	0	7,400	0
Actuator No. 4				
50-percent Open	0	0	1,450	0
75-percent Open	0	-	4,210	-
100-percent Open	0	0	0	0

NOTE: Specification maximum leakage rate with actuator 100-percent open is 10 cc/hr for both the actuator piston and shaft seals (Ref. 18).

TABLE IV
THRUST CHAMBER VALVE AVERAGE OPERATING TIMES
(Including the Extreme Envelope)

Valve Set	Propellant Temperature, °F	Initial Open, msec	Full Open, msec	Opening Time, msec	Initial Close, msec	Full Close, msec	Closing Time, msec
TCV Mod I-D, S/N 122				TEST PERIOD FL			
1	25 to 35	142^{+108}_{-22}	875^{+165*}_{-205}	732^{+178*}_{-202*}	137^{+53}_{-77}	542^{+98*}_{-162*}	398^{+172*}_{-78*}
2	25 to 35	97^{+23}_{-17}	495^{+45}_{-95}	402^{+28}_{-72*}	293^{+57}_{-173}	912^{+48}_{-132}	613^{+97*}_{-103}
3	25 to 35	78^{+12}_{-8}	436^{+34}_{-36*}	359^{+31}_{-29*}	289^{+31}_{-49}	819^{+31}_{-39}	525^{+35}_{-25}
4	25 to 35	113^{+107}_{-23}	882^{+78*}_{-62}	768^{+92*}_{-48}	213^{+77}_{-113}	625^{+15*}_{-35*}	402^{+28*}_{-102*}
TCV Mod I-E, S/N 126				TEST PERIOD FQ			
1	30 to 35	137^{+53}_{-37}	861^{+19}_{-31}	716^{+44}_{-31}	139^{+56}_{-49}	550^{+10}_{-10}	363^{+17}_{-13}
	110 to 115	130^{+60}_{-40}	757^{+73}_{-27}	627^{+23}_{-17}	159^{+21}_{-19}	494^{+16}_{-24}	335^{+25}_{-25}
2	30 to 35	109^{+46}_{-19}	562^{+18}_{-22}	450^{+30}_{-40}	241^{+71}_{-111}	792^{+28}_{-32}	516^{+44}_{-26}
	110 to 115	128^{+32}_{-28}	508^{+62}_{-28}	380^{+30}_{-20}	242^{+8}_{-22}	723^{+17}_{-23}	482^{+8}_{-22}
3	30 to 35	77^{+33}_{-17}	560^{+20}_{-20}	478^{+32}_{-48}	233^{+57}_{-83}	781^{+19}_{-21}	516^{+24}_{-26}
	110 to 115	88^{+22}_{-18}	486^{+54}_{-16}	398^{+42}_{-28}	233^{+17}_{-13}	708^{+12}_{-8}	474^{+16}_{-4}
4	30 to 35	97^{+33}_{-17}	870^{+30}_{-30}	764^{+26}_{-54}	140^{+70}_{-60}	573^{+17}_{-33}	379^{+11}_{-9}
	110 to 115	105^{+35}_{-15}	723^{+67}_{-33}	618^{+32}_{-28}	158^{+12}_{-8}	498^{+12}_{-18}	339^{+21}_{-9}
Spec: (Ref. 18)	Sets 1 and 4		650 – 950	550 – 800		430 – 630	325 – 425
	Sets 2 and 3		450 – 750	350 – 550		675 – 975	475 – 675

<u>DEFINITIONS OF OPERATING TIMES</u>:

Initial Open – Time from fire signal to initial movement.
Full Open – Time from fire signal to full open.
Opening Time – Time from initial movement to full open.

Initial Close – Time from shutdown signal to initial movement.
Full Close – Time from shutdown signal to full closed.
Closing Time – Time from initial movement to full closed.

*Out of Specification

TABLE V
COMBUSTION OVERPRESSURE SUMMARY

Firing Number	TCV Bank Selected	Overpressure, percent
FL-02*	B	13
	Drained and Purged Propellant Lines and TCV	
-04*	AB	26
-05	AB	17
-07	AB	11
-08	AB	18
	Drained and Purged Propellant Lines and TCV	
-09A*	A	19
-09B	A	15
-09C	A	8
-09D	A	11
-10A*	B	9
-10B	B	7
-10C	B	8
-10D	B	9
-11A	AB	21
-11B	AB	28
-11C	AB	23
-11D	AB	21

*Dry Starts

APPENDIX III
TCV LEAKAGE CHECK PROCEDURES

Each of the eight balls in the TCV (Section 2.1.1) is equipped with an upstream, a downstream, and shaft seals (Fig. 3). The purpose of the upstream and downstream seals is to prevent propellant from leaking past the valve balls into the injector manifolds when the valve balls are in the closed position. The purpose of the shaft seals is to prevent any leakage along the shafts to the inside cavity of the valve housing.

Leakage checks of the various TCV seals were conducted prior to test periods FK and FP and after test periods FL and FQ. The procedures used to determine the leakage rates are included in the following sections. All rates were determined by applying GN_2 pressure across the seal, or seals, in question and measuring the leakage on the downstream side with a water displacement leak meter. The leakage rates obtained at the various pressures applied are shown in Table II. Also shown, where applicable, are the maximum specification leakage rates (Ref. 18).

Downstream Ball Seal

The downstream seals on each of the eight balls were individually leak checked by applying equal GN_2 pressures on both sides of the upstream ball seals. (It was necessary to apply equal pressure across the upstream ball seal to prevent it from being unseated by reverse pressure.)

Upstream Ball Seal

The upstream seals on each of the eight balls were individually leak checked by applying pressure to the upstream side of each ball and measuring the leakage at the ports to the cavities between the ball upstream and downstream seals.

Ball Shaft Seals (Balls Closed)

Leakage past the ball shaft seals was measured in ball pairs; i.e., the two upstream oxidizer ball shaft seals were leak checked as a unit, the two downstream oxidizer ball shaft seals were checked as a unit, the two upstream fuel ball shaft seals were checked together, and the two downstream fuel ball shaft seals were leak checked together. In each case, the upstream side of a pair of like propellant balls was pressurized and an equal pressure was applied to the cavity between the upstream and downstream ball seals of

each ball. Leakage past the pair of shaft seals was measured at the exit of the shaft seal drain manifolds (Fig. 2).

Ball Shaft Seal (Balls Open)

The sum of the leakage past the four ball shaft seals on a particular propellant side with all four balls open was determined by pressurizing the flow passages of the valve and measuring the leakage at the exit of the ball shaft seal drain manifold.

APPENDIX IV
ENGINE PERFORMANCE

PERFORMANCE DATA ACQUISITION, REDUCTION PROCEDURE, AND UNCERTAINTY ANALYSIS

Primary performance parameters were recorded on magnetic tape in continuous, modulated frequency form. Digital computers were used to decode the magnetic tape, produce engineering units data tabulations, and compute performance from the reduced data as follows:

1. Steady-state engine performance,
2. Incremental and total impulse during ignition,
3. Incremental and total impulse during shutdown, and
4. Incremental and total impulse for each impulse bit operation.

The equations used for engine performance calculations were in accord with general practice, with modification to account for the area variation caused by ablation of the thrust chamber throat. Steady-state performance calculations were made from measured data which were averaged over 4-sec time intervals for firings of 10-sec or longer duration.

The estimated errors (two standard deviations) in the measured parameters and engine performance calculations were determined statistically from the in-place calibrations and from the methods outlined in Refs. 17 and 19, and were as follows:

Parameter	2σ Error, ± percent
F_a	0.30
p_c	0.50*
$\dot{w}_f$	0.44
$\dot{w}_o$	0.42
p_{cell}	3.70
$\dot{w}_t$	0.30
F_v	0.30
I_{sp_v}	0.42

*The estimated chamber pressure error does not include data from the FL test period which was instrumented for combustion overpressure measurement.

Engine Performance

Nonuniform variations of the nozzle effective throat area during a firing and the impossibility of measuring throat area between firings during a particular test period necessitated calculation of characteristic velocity (c^*) using the following assumptions:

1. Characteristic velocity, corrected to a mixture ratio of 1.6, is constant for a particular injector and chamber combination.
2. Characteristic velocity is a function of mixture ratio, propellant temperature, and combustion chamber pressure.

The initial characteristic velocity (c^*_i) was calculated using (1) the measured data from the initial firing, (2) the pretest measured nozzle throat area, and (3) the relationship

$$c^*_i = p_c \, A_t \, g_c/\dot{w}_t$$

The c^* for nominal operating conditions (c^*_{nom}) of O/F = 1.6, propellant temperature of 70°F, and a combustion chamber pressure of 99 psia was derived using the following empirical equation supplied by AGC:

$$\begin{aligned} c^*_{nom} = c^*_i &+ 870.5\,[1.6 - (O/F)] + 273.83\,[(O/F)^2 - 2.56] \\ &+ 0.31878\,(p_c - p_{c_{nom}}) - 12.853\,(T_p - 70) \\ &+ 0.07414\,(T_p^2 - 4900) - 5.466\,[(O/F)\,T_p - 112] \\ &- 0.03119\,[(O/F)\,T_p^2 - 7840] \end{aligned}$$

This c^*_{nom} was retained as representative of the injector/chamber assembly and was used for data reduction for the remaining tests. The c^* for each individual firing (c^*_s) during which inlet conditions were nonstandard was calculated using the above equation solved for c^*_i (= c^*_s) where the input values of T_p, p_c, and O/F were measured values.

The throat area of the nozzle for subsequent firings was calculated using the c^*_s derived above, the measured chamber pressure, and the measured propellant flow rates in the relationship:

$$A_{t_{calc}} = c^*_s \, \dot{w}_t/g_c p_c$$

The measured axial thrust was corrected to vacuum conditions using measured test cell pressure as follows:

$$F_v = F_a + p_{cell} A_e$$

This vacuum thrust was used with calculated nozzle throat area and measured chamber pressure to determine a vacuum thrust coefficient as follows:

$$C_{F_v} = F_v / p_c \cdot A_{t_{calc}}$$

Vacuum specific impulse was calculated from

$$I_{sp_v} = F_v / \dot{w}_t$$

where

$$\dot{w}_t = \dot{w}_o + \dot{w}_f$$

Ignition and Shutdown Transient Performance Data

Transient performance data were processed using the AEDC Transient Impulse Computer Program RDR-38 to determine the characteristics of the impulse associated with the transient portions of the engine firings (start and shutdown).

The total impulse of the start transient covered the time period from ignition (chamber pressure ≥ 1 psia) to 100 percent of steady-state vacuum thrust. The impulse was derived using the vacuum thrust coefficient (not corrected to standard inlet conditions), throat area, and measured chamber pressure in the relationship,

$$I_t = C_{F_v} A_t \int_{t_1}^{t_2} p_c \, dt$$

in which the values of C_{F_v} and A_t were input from the steady-state performance data of the firing and were assumed constant throughout the transient.

The total impulse of the shutdown transient was calculated in a similar manner except that the integral covered the time period from the shutdown signal to 0.3-psia chamber pressure.

Steady-state performance was not calculated for firings of less than 7-sec duration. For these short firings, the values of C_{F_v} and A_t were obtained from the steady-state performance of the firing conducted nearest the transient of interest at the same operating conditions (p_c, O/F, and valve bank).

Intermediate impulse values of the start and shutdown transients were also derived at 10-percent intervals of steady-state chamber pressure up to the 100-percent level. The computer program also calculated the time at which the percentage thrust levels occurred, the thrust rise or decay rates, and the integrated impulse at the specified percentage levels of steady-state chamber pressure.

Measured combustion chamber pressure of the ignition transient was reduced at 0.005-sec intervals (200 values/sec) from the magnetic tape data records obtained from a close-coupled strain-gage-type chamber pressure transducer. Shutdown combustion chamber pressure was reduced at 0.02-sec intervals (50 values/sec). The close-coupled chamber pressure transducer data included an alternate expanded-range channel which was used for improved accuracy at pressures below 12 psia.

Impulse Bit Firings

The method used to calculate the total impulse of the impulse bit firings (duration $\leq$ 1 sec) was identical to the method used for the ignition and shutdown transients except that the impulse was totaled for the entire firing from ignition through thrust decay to p_c = 0.3 psia. Since the impulse bit firings were too short to establish steady-state engine performance, C_{F_v} and A_t were obtained from the nearest steady-state firing at the same engine operating conditions (p_c, O/F, and valve bank selection).

The total propellant quantity for impulse bit operation was determined from total flowmeter signal cycles (recorded on magnetic tape) and the flowmeter calibration factor constant for the normal flow rate range. The total quantity is somewhat in error because the flowmeter transient characteristics and low flow rate nonlinearities were neglected.

IGNITION TRANSIENT

The total vacuum impulse (lb_f-sec) developed during the engine ignition and shutdown transients was determined by the method discussed in the preceding section. A tabulation of the ignition impulse is presented in Table IV-1. A summary

of the average ignition impulse obtained during the FQ series using 30 and 110°F propellants is presented below. The FL series test data are not included in the summary below because the high-frequency response transducer used to measure the chamber pressure (Section 2.3.1) yielded data known to be approximately 10 percent low. The FP data are not included because the single firing made during that test period was a single-bore start and is, therefore, not compatible with the remaining data.

The ignition impulse ($p_c \approx 1.0$ psia to 90 percent of steady-state p_c) is shown below.

			Specification (Ref. 18)
Target p_c, psia	110	117	99
Target Propellant Temperature, °F	30 to 35	110 to 115	70
Number of Data Points	12	7	-
Average Impulse, lb_f-sec	239	767	100 to 600
Run-to-Run Deviation	+50 -61	+218 -143	±200
2σ, percent	±29.2	±36.2	-
Average Duration, msec	552	503	450 to 650
Run-to-Run Deviation	+7 -7	+10 - 7	-
2σ, percent	±2.1	±2.5	-

The temperature and pressure limitations of the specification preclude a direct comparison of the data with the specification. The specification values are presented for reference only.

Generally it was found that the time from the ignition signal to the first indication of chamber pressure was longer for the colder propellants but that the thrust rise rates, once ignition commenced, were more rapid. Even though ignition occurred later with the cold propellants, the rise rate was higher because of the larger preignition propellant accumulation; consequently, the ignition transient impulse was less than that obtained with hot propellants. Part of the reason for the longer ignition delay with the cold propellants can be attributed to slower TCV operation (Section 4.2.3). As the data in Table IV indicate, the average opening times were 90 and 146 msec longer for valve sets 1 and 4,

respectively, using the colder propellants. The average combustion overpressure (as determined by the Transient Impulse Program, discussed in the previous section, was $8.8^{+4.9}_{-3.7}$ percent with the 30°F propellants as compared with $5.8^{+3.0}_{-4.2}$ percent with the 110°F propellants.*

The ignition impulse during firing FQ-24 (1979 lb_f-sec) was 2.5 times the average value obtained from the other firings conducted under similar conditions. This was the first firing in the series made at a 117-psia chamber pressure. (These data are not included in the impulse summary above.) Opening times for all four valve sets were less (≈ 30 msec) than the average values, although valve set 1 did not initially open until 160 msec after FS-1 as compared with the average time of 130 msec. The time from FS-1 to ignition was 293 msec compared with the average of 313 msec. As indicated by the chamber pressure history in Fig. IV-1, the rise rate was 13 percent above average up to approximately 70 psia and then slowed to approximately 25 percent of the average rise rate at 90 percent of steady-state chamber pressure. This greatly increased the time required to reach 90-percent thrust, which resulted in the abnormally high impulse. It was surmised that the rate of propellant accumulation in the chamber was insufficient to maintain the high initial reaction rate, particularly since ignition occurred approximately 20 msec earlier than the average time.

Firing FQ-20 had an abnormal ignition transient chamber pressure profile (Fig. IV-1). It was the first firing after refill of the F-3 fixture with 110°F propellants. Ignition did not occur until approximately 348 msec after FS-1 compared with the average time of 313 msec. After ignition, the chamber pressure increased to approximately 33 psia and then decayed to about 16 psia before continuing to increase at a slower than normal rate up to the steady-state level. The total cycles of the flowmeters from FS-1 to FS-1 plus 603 msec were 170 and 32 percent greater than the average for the oxidizer and fuel, respectively, although the propellant tank pressure settings were normal. It was ascertained that propellants were not properly bled into the engine prior to firing FQ-20 and consequently, the gas bubbles in the propellant lines resulted in the abnormal chamber pressure profile.

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*These average values of combustion overpressure are smaller than the overpressures recorded during test period FL (Table V) because of the difference in chamber pressure instrumentation (Section 2.3.1).

SHUTDOWN TRANSIENT

A tabulation of the shutdown impulse developed during each firing of duration greater than 1.0 sec is presented in Table IV-II. A summary of the test period FQ shutdown average impulse data for dual-bore operation and for the different temperature and chamber pressure combinations is presented below. None of the data can be compared directly with the specification because the firings were intentionally made outside the interface pressure and propellant temperature specification.

The shutdown impulse (FS-2 to 1 percent of steady-state p_c) is shown below.

					Specification (Ref. 18)
Target p_c, psia	100	110	110	117	99
Target Propellant Temperature, °F	110^{+5}_{-0}	30^{+5}_{-0}	110^{+5}_{-0}	110^{+5}_{-0}	70
Number of Data Points	1	2	3	3	---
Average Impulse, lb_f-sec	10,255	11,768	10,648	11,410	800 to 13,000
Run-to-Run Deviation	---	+238 -238	+209 -122	+74 -80	±500
Average Duration, sec	2.678	3.100	1.499	1.382	0.750 to 1.100
Run-to-Run Deviation	---	+0.511 -0.511	+0.029 -0.035	+0.032 -0.056	---

Based on the limited data available, the tests using 30°F propellants had the lowest chamber pressure decay rates and, thus, the highest shutdown impulse values. Conversely, the firing at 100-psia steady-state chamber pressure with 110°F propellants had the higher chamber pressure decay rate and, consequently, the least shutdown impulse. The run-to-run deviations ranged from 0.6 to 2.0 percent of the average shutdown impulse.

IMPULSE BIT OPERATION

The total impulse of the bit impulse firings (duration $<$ 1.0 sec) was determined by the method discussed in the previous section. A tabulation of the impulse developed during each impulse bit firing appears in Table IV-III.

Total impulse as a function of firing duration (FQ series) for the different target chamber pressures and propellant temperatures is presented in Fig. IV-2. The magnitude of the total impulse was a near-linear function of the firing duration. The average total impulse values developed with dual-bore TCV configuration during the FQ series for the different target chamber pressures and propellant temperature combinations are presented below (the fact that there were slight variations in the durations of the five firings in each group has been disregarded).

The bit impulse [ignition ($p_c \approx 1.0$ psia) to end of tailoff ($p_c \approx 0.3$ psia)] is shown below.

Target p_c, psia	110	110	110	117
Target Propellant Temperature, °F	30^{+5}_{-0}	30^{+5}_{-0}	30^{+5}_{-0}	110^{+5}_{-0}
Average Impulse, lb_f-sec	2354	9637	22,573	24,066
Run-to-Run Deviation	+200 -360	+232 -394	+ 82 -182	+179 -370
Average Duration, sec	0.41	0.60	1.01	1.01

As would be expected, the run-to-run repeatability of the total impulse generally improves with increased firing duration. Examination of the average data for the 1.1-sec duration firings indicates that the average total impulse obtained with 110°F propellants and target chamber pressure of 117 psia was 6.6 percent greater than that obtained with 30°F propellant at 110 psia. A considerable portion of this difference results from the higher chamber pressure level; however, as indicated by the data in Table IV, the valve opened faster with the 110°F propellants. The closing times, however, were not affected as much by propellant temperature. Consequently, the valve was full open longer during the tests which used 110°F propellants, and this contributed to the aforementioned increase in the total impulse.

The propellant flow (lb_m) during bit operation was determined using integrated flowmeter cycles, the propellant specific gravity, and the flowmeter calibration constant.

The propellant flows obtained during the FL and FQ series are presented as a function of firing duration in Fig. IV-3. The FL series data indicate that the propellant flow during a 1.0-sec firing, using either TCV bank A or B, was approximately 23 and 11 percent less, respectively, than the quantities flowed using dual-bore valve configuration. The FQ series data were obtained using dual-bore TCV configuration. These data indicate that the average mass of oxidizer and

fuel flow during a 1.0-sec firing with 30°F propellants at a 110-psia chamber pressure was approximately 49 and 27 lb_m, respectively. With 110°F propellants and 117-psia chamber pressure, the average mass of oxidizer and fuel increased 4 and 13 percent, respectively. The data in Fig. IV-3 also indicate that a firing duration must exceed approximately 300 msec to indicate any flow.

STEADY-STATE PERFORMANCE

A steady-state performance summary of measured* data is included in Table IV-IV. Because of the uncertainty of the combustion chamber throat area, the I_{sp_v} data are considered the most accurate indication of performance.

The performance specification established by Ref. 18 specifies a thrust envelope (for thrust adjusted to standard inlet conditions**) as a function of accumulated firing time on the ablative chamber. The thrust data from all firings for both the Mod I-D and I-E TCV's which were tested on the same chamber, are included in Fig. IV-4a. A 3-percent decay in the dual-bore TCV operation thrust occurred after firing FP-01; however, all thrust data, both dual- and single-bore, are within the specification. Because the vacuum specific impulse, presented in Fig. IV-4b, corresponding to the above thrust data, reveals no such degradation in performance, it was concluded that the engine balance interface orifices, which were resized between test periods FP and FQ (see Section 2.1.1), resulted in the 3-percent thrust degradation.

Measured vacuum specific impulse values obtained during testing of both the Mod I-D and Mod I-E TCV's at various thrust chamber pressures and propellant temperatures are shown in Table IV-V. The values shown are averages of all firings falling within the target chamber pressure and propellant temperature group. Values are also shown for the Mod I-C TCV (Ref. 14) for a comparison.

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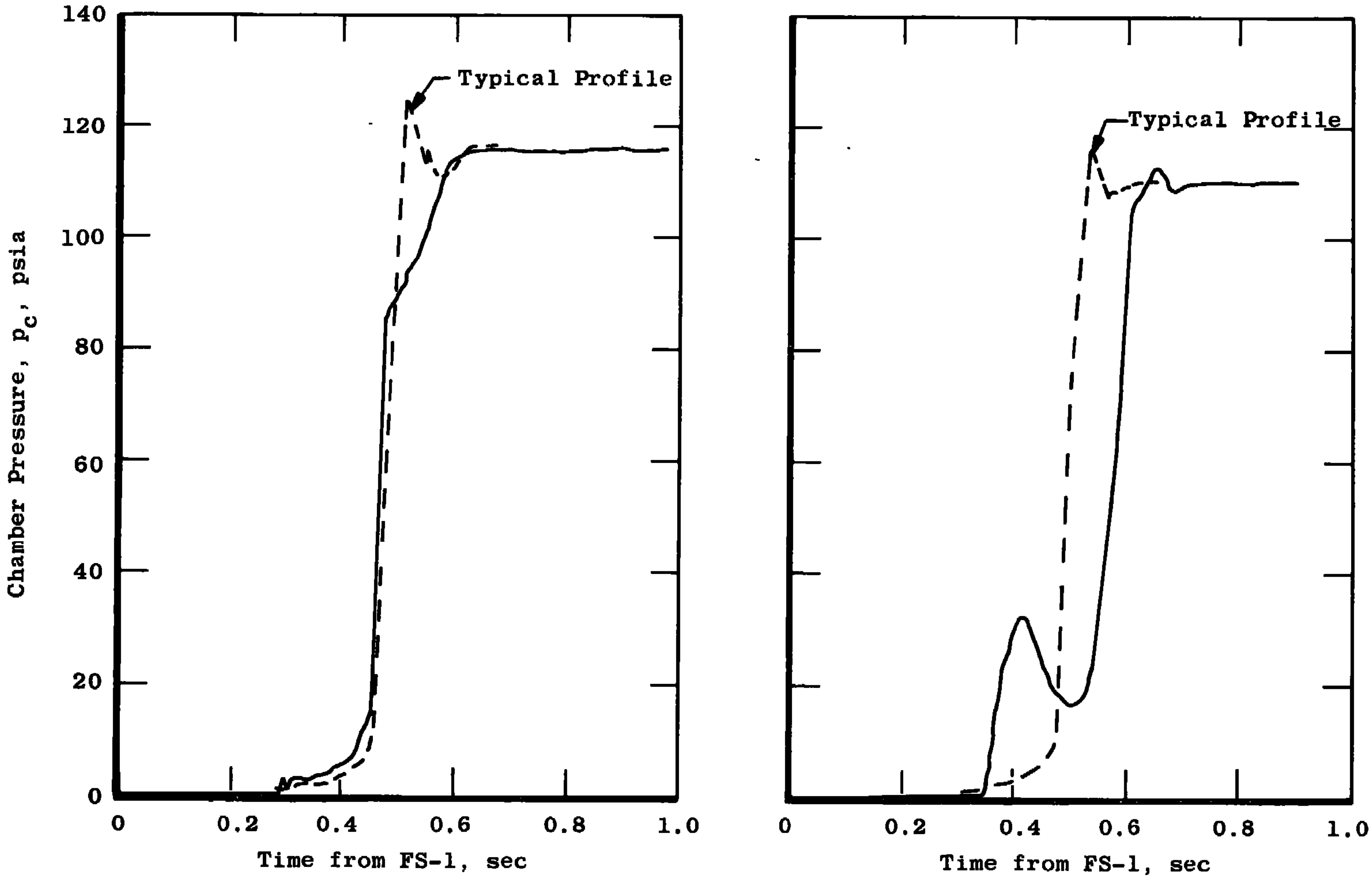
*Corrected to vacuum but not to standard inlet conditions.

**Standard inlet conditions are:
Propellant temperature = 70°F
Interface pressures, psia

	Dual Bore	Single Bore
Oxidizer	162	160
Fuel	169	166

The equations for performing the data adjustment are contained in Ref. 18.

A tendency toward increasing I_{sp_v} with both chamber pressure and propellant temperature is evident. Based on the limited data available, it is concluded that the modifications to the TCV's have not affected engine performance.



a. Firing FQ-24 b. Firing FQ-20

Fig. IV-1 Abnormal Ignition Transients

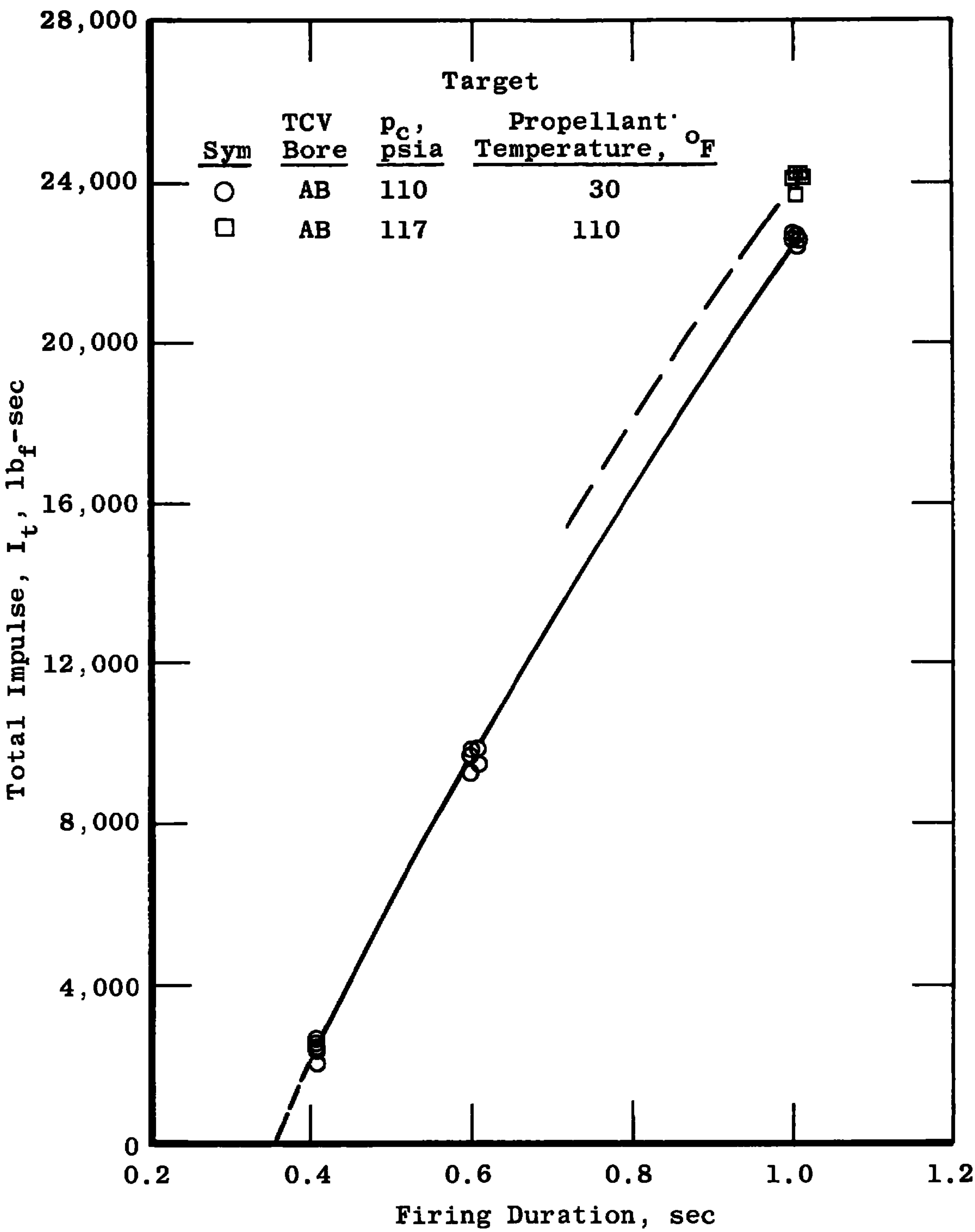
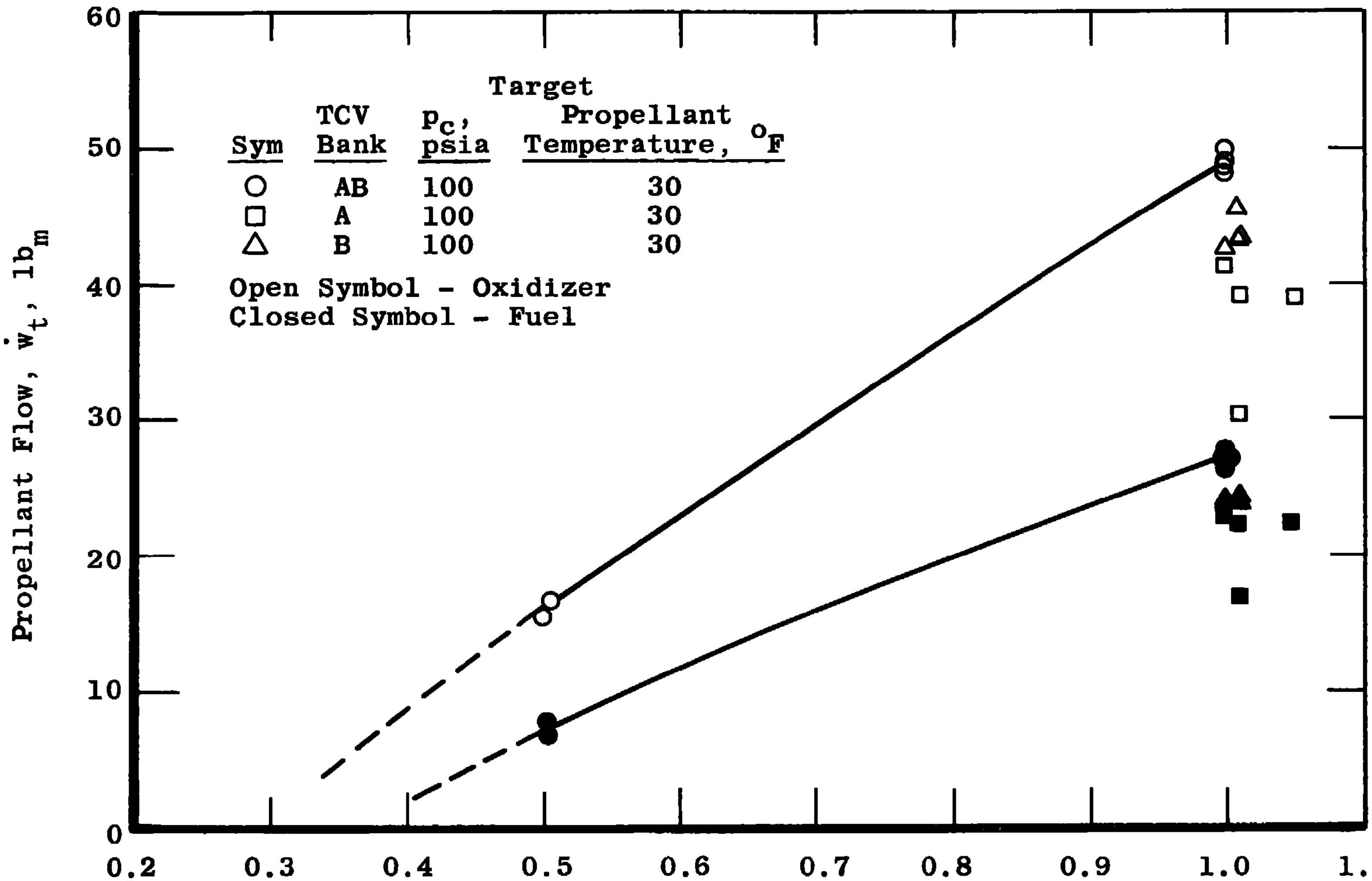
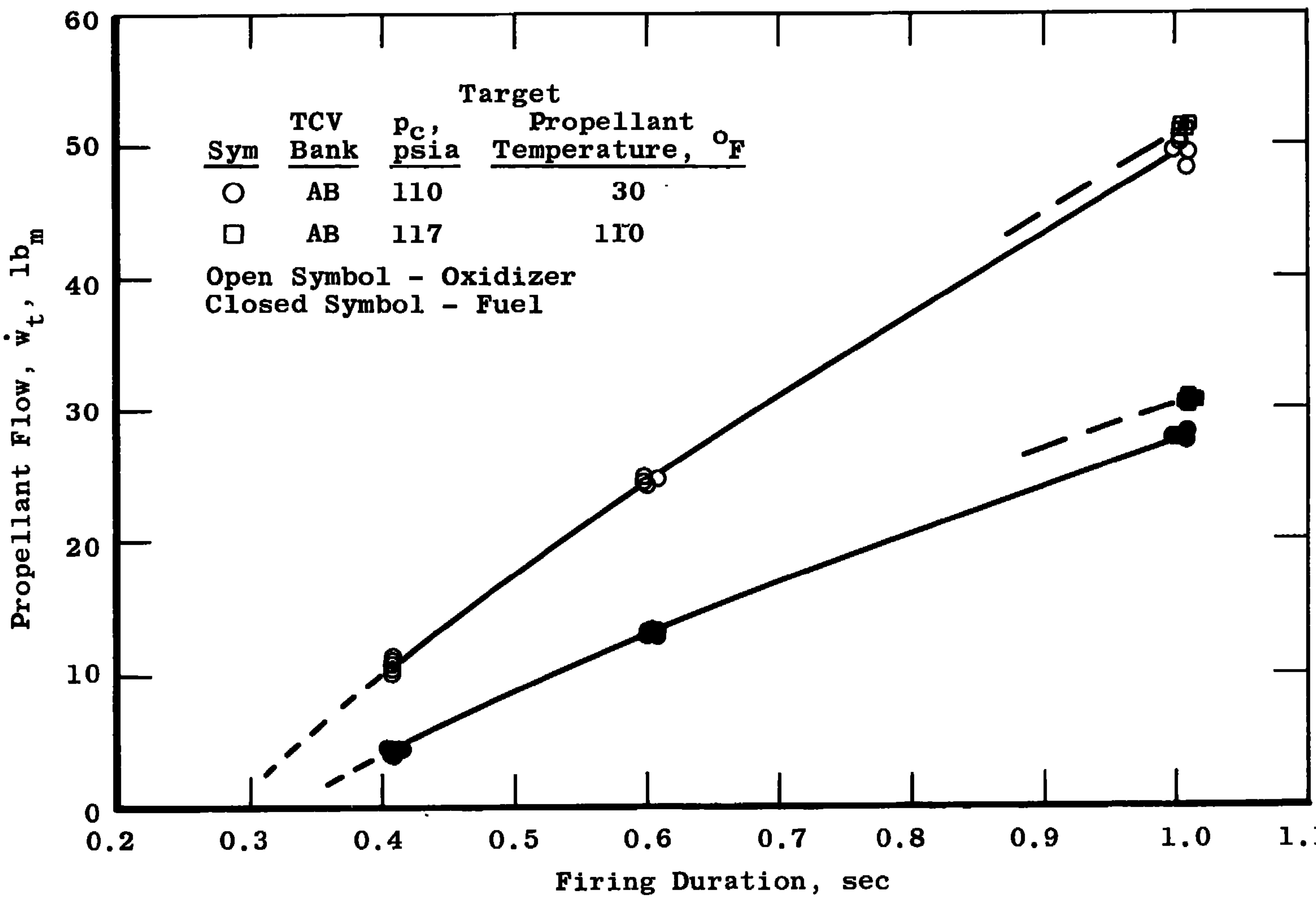


Fig. IV-2 Total Impulse of Impulse Bit Firings (FQ Test Series)

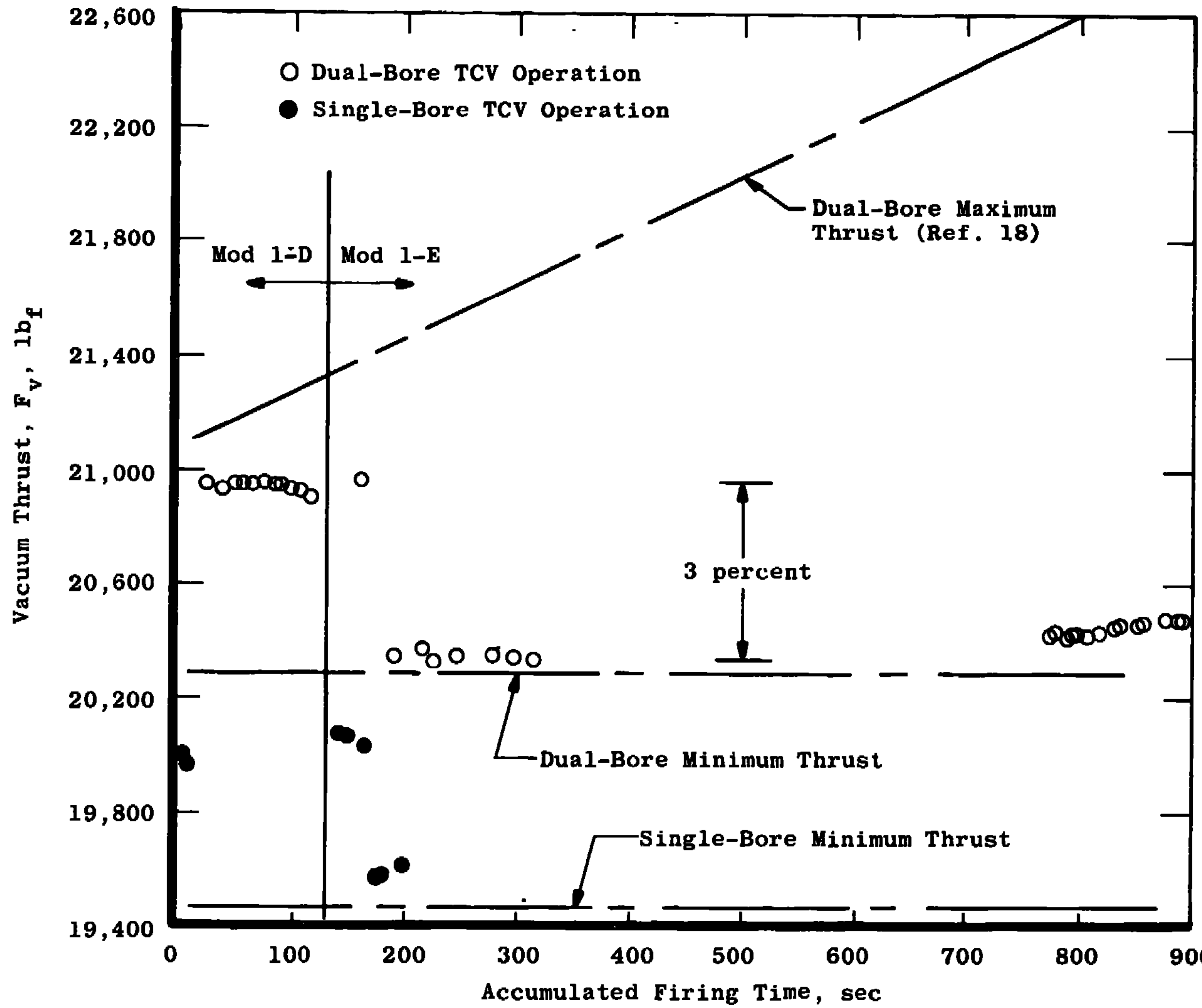


a. Mod 1-D

Fig. IV-3 Propellant Flow as a Function of Firing Duration

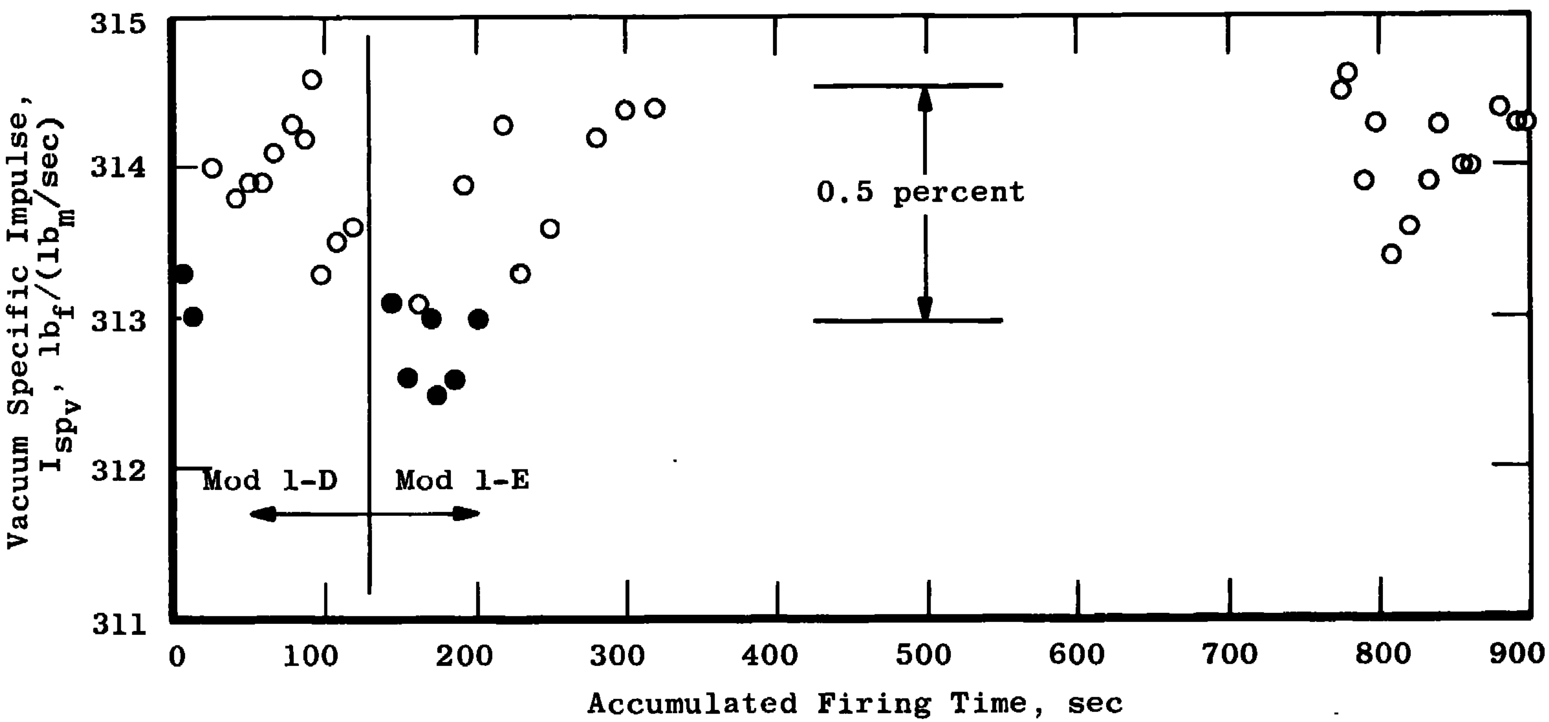


b. Mod 1-E
Fig. IV-3 Concluded



a. Thrust

Fig. IV-4 Steady State Performance History (Adjusted to Standard Inlet Conditions)



b. Specific Impulse

Fig. IV-4 Concluded

TABLE IV-I
IGNITION IMPULSE SUMMARY

Test Number	Engine Serial Number	TCV Bank	Target Chamber Pressure Level, psia	From FS-1 to 90-percent of Steady-State Thrust	
				Time, sec	Impulse, lb-sec
FL-01	054G	A	86	0.674	See Note 1
-02		B	86	0.630	
-03		AB	90	0.567	
-04				0.636	
-05				0.560	
-06				0.584	
-07				0.562	
-08				0.570	
-09A		A	86	0.658	
-09B				0.644	
-09C				0.625	
-09D				0.628	
-10A		B		0.661	
-10B				0.645	
-10C				0.640	
-10D				0.628	
-11A		AB	90	0.546	
-11B				0.538	
-11C				0.533	
-11D				0.529	
FP-01	054H	A	100	0.659	125
FQ-02	054I	A	100	0.674	314
-03		AB	110	0.547	178
-04				0.548	214
-05				0.562	212
-06				0.554	244
-07				0.547	232
-08				0.555	203
-09				0.556	263
-10				0.556	277
-11				0.545	271
-12				0.545	270
-18				0.546	218
-19				0.559	289
-20				0.599	1566(3)
-21				0.563	1166
-22				0.520	720
-23			100	0.522	713
-24			117	0.555	1979(3)
-25				0.505	811
-26				0.502	642
-27				0.513	985
-28				0.508	903
-29				0.501	741
-30				0.496	664
-31				0.496	624

Notes: (1) The test period FL chamber pressure data were in error by approximately 10 percent. See section 4.3 of this report.

(2) Firings FQ-13 through 17 are not included because the firing durations were too short for the TCV to fully open and for the chamber pressure to attain 90 percent of steady state.

(3) Nontypical (See Fig. IV-I)

TABLE IV-II
SHUTDOWN IMPULSE SUMMARY

Test Number	Engine Serial Number	TCV Bank	Target Chamber Pressure Level, psia	From FS-2 to 1-percent of Steady-State Thrust	
				Time, sec	Impulse, lb-sec
FL-01	54G	A	86	1.326	See Note 1, Table IV-I
-02		B	86	1.063	
-04		AB	90	0.905	
-05			90	0.539	
-07			90	1.275	
-08			90	1.315	
FP-01	54H	B	100	2.382	9,676
FQ-02	54I	B	100	2.491	10,299
-18		AB	110	3.611	12,006
-19				2.588	11,530
-20				1.528	10,857
-21				1.464	10,560
-22				1.504	10,526
-23			100	2.678	10,255
-24			117	1.326	11,484
-25				1.414	11,417
-26				1.406	11,330

Note: Only those firings of 1-sec duration or longer are included in this table.

TABLE IV-III
BIT IMPULSE SUMMARY

Test Number	Engine Serial Number	TCV Bank	Target Chamber Pressure Level, psia	Test Duration, sec	Impulse, lb_f-sec
TL-03	54G	AB	90	0.505	See Note 1, Table IV-I
-06		AB	90	0.500	
-09A		A	86	1.000	
-09B				1.010	
-09C				1.050	
-09D				1.010	
-10A		B		1.010	
-10B				1.000	
-10C				1.010	
-10D				1.010	
-11A		AB	90	1.000	
-11B				1.000	
-11C				1.000	
-11D				1.000	
FQ-03	54I	AB	110	1.010	22,646
-04				1.010	22,571
-05				1.010	22,391
-06				1.005	22,602
-07				1.000	22,655
-08				0.600	9,243
-09				0.610	9,447
-10				0.600	9,771
-11				0.600	9,853
-12				0.610	9,869
-13				0.410	1,994
-14				0.410	2,354
-15				0.410	2,425
-16				0.410	2,445
-17				0.410	2,554
-27			117	1.005	23,696
-28				1.010	24,089
-29				1.010	24,245
-30				1.010	24,207
-31				1.010	24,093

TABLE IV-IV
ENGINE PERFORMANCE SUMMARY
(Measured Data)

Test Number	Engine S/N	Averaging Period	Propellant Pressures, psia p_{o_t}	p_{o_l}	p_{f_t}	p_{f_l}	Flow Rates, lb_m/sec $\dot{w}_o$	$\dot{w}_f$	$\dot{w}_t$	O/F	T_o, °F	T_f, °F	p_c, psia	F_v, lb_f	p_{cell}, psia	$A_{t_{calc}}$, in.^{2}	I_{sp_v}, lb_f-sec/lb_m	c^*_s, ft/sec	C_{F_v}
FL-01	54G	2-6	170.56	166.60	174.00	174.12	40.99	25.17	66.16	1.628	30.00	30.53		20,674	0.0797		312.47		
FL-02	54G	2-6	170.37	166.33	170.05	170.36	41.04	24.59	65.64	1.669	30.00	30.77		20,492	0.0744		312.21		
FL-04	54G	6-10	172.20	167.08	170.90	170.63	43.20	25.66	68.86	1.683	30.00	30.75		21,566	0.0714		313.17		
FL-05	54G	6-10	171.62	166.15	170.73	170.12	42.92	25.66	68.58	1.672	30.00	30.74		21,469	0.0701		313.05		
	54G	14-18	171.71	166.04	170.79	170.05	42.94	25.68	68.62	1.672	30.00	30.75		21,486	0.0718		313.11		
	54G	22-26	171.71	165.89	170.83	169.95	42.92	25.63	68.55	1.674	30.00	30.75		21,466	0.0734		313.14		See
	54G	30-34	171.75	165.74	170.86	169.85	42.89	25.58	68.48	1.677	30.00	30.75	See	21,453	0.0752	See	313.29	See	Note
	54G	38-42	171.76	165.60	170.90	169.77	42.81	25.60	68.41	1.672	30.00	30.75	Note 1	21,447	0.0775	Note 1	313.49	Note 1	1
	54G	46-50	171.75	165.42	170.90	169.66	42.79	25.60	68.39	1.671	30.00	30.75		21,436	0.0800		313.44		
	54G	50-54	171.74	165.34	170.94	169.61	42.71	25.57	68.28	1.671	30.00	30.75		21,430	0.0812		313.36		
FL-07	54G	6-10	172.96	166.22	171.38	170.17	43.07	25.61	68.68	1.682	30.00	30.98		21,464	0.0717		312.50		
	54G	14-18	173.00	166.08	171.38	170.03	42.99	25.59	68.58	1.679	30.00	30.98		21,450	0.0736		312.72		
FL-08	54G	6-10	173.83	165.98	172.18	170.02	42.92	25.56	68.48	1.679	30.00	30.95		21,418	0.0723		312.75		
FP-01	54H	2-6	177.26	164.83	176.20	171.13	40.91	24.93	65.84	1.641	31.74	32.73	99.03	20,576	0.0899	121.20	312.49	5864.7	1.714
	54H	6-10	177.25	164.65	176.12	171.03	40.93	24.95	65.88	1.640	31.83	32.82	98.98	20,559	0.0778	121.35	312.02	5865.0	1.712
	54H	14-18	177.30	163.46	176.12	170.57	42.59	25.82	68.42	1.650	31.88	32.93	102.96	21,377	0.0728	121.08	312.45	5862.3	1.715
	54H	26-30	177.20	164.22	176.11	170.71	40.67	24.89	65.56	1.634	31.93	33.12	99.08	20,483	0.0713	120.66	312.41	5866.5	1.713
FQ-02	54I	2-6	171.91	166.90	176.10	172.60	40.09	24.73	64.83	1.621	31.50	31.80	98.09	20,225	0.0866	120.52	311.95	5866.7	1.710
	54I	6-10	171.90	167.10	176.20	172.60	40.02	24.73	64.75	1.618	31.50	31.90	98.12	20,261	0.0747	120.34	312.94	5867.3	1.716
	54I	14-18	171.90	166.30	176.20	172.00	41.27	25.70	66.97	1.606	31.60	32.06	101.6	20,987	0.0697	120.26	313.34	5868.4	1.718
	54I	26-30	171.90	166.80	176.20	172.20	39.92	24.75	64.67	1.613	31.60	32.20	98.16	20,253	0.0678	120.15	313.21	5868.6	1.717
FQ-18	54I	6-10	197.00	187.18	198.80	192.40	45.20	27.71	72.91	1.631	32.10	32.70	110.60	22,906	0.0778	120.14	314.17	5862.9	1.724
FQ-19	54I	6-10	197.40	186.40	196.10	193.10	44.97	27.93	72.90	1.609	31.20	35.00	110.03	22,832	0.0743	120.85	313.18	5868.4	1.717
	54I	26-30	197.30	185.80	195.10	191.80	44.88	27.76	72.64	1.616	31.20	35.00	109.76	22,770	0.0712	120.69	313.46	5867.5	1.719
	54I	58-62	197.30	184.90	195.00	191.10	44.64	27.66	72.30	1.614	31.20	35.00	109.62	22,710	0.0784	120.28	314.12	5868.0	1.722
	54I	78-82	197.30	184.40	195.10	190.80	44.48	27.64	72.12	1.609	31.20	35.10	109.46	22,665	0.0819	120.18	314.27	5868.7	1.723
	54I	98-102	197.20	183.90	195.10	190.60	44.36	27.61	71.97	1.607	31.20	35.10	109.38	22,618	0.0839	120.04	314.23	5869.2	1.722
	54I	198-202	196.80	181.20	195.10	189.00	43.79	27.47	71.26	1.594	31.79	35.20	108.55	See	0.0892	119.84	See	5872.4	1.723
	54I	298-302	196.40	188.30	194.90	193.90	45.10	27.89	72.99	1.617	32.43	35.21	111.14	Note	0.0954	119.80	Note	5868.7	1.726
	54I	398-402	195.40	185.80	194.80	192.70	44.60	27.82	72.42	1.603	32.42	35.26	110.33	2	0.0987	119.80	2	5871.2	1.729
	54I	546-550	194.50	182.00	194.90	190.70	43.86	27.77	71.63	1.579	32.75	35.39	108.90		0.132	120.14		5875.9	1.732
FQ-20	54I	4-8	--	189.02	--	194.90	43.78	27.66	71.44	1.583	117.00	(117)[3]	109.18	22,434	0.0785	120.42	313.99	5920.9	1.706
	54I	6-10	--	188.90	--	194.80	43.76	27.67	71.43	1.581	117.00	(117)	109.08	22,436	0.0761	120.53	314.06	5921.3	1.706
FQ-21	54I	4-8	197.20	189.10	196.70	194.80	44.00	27.67	71.67	1.589	108.60	(113)	109.22	22,482	0.0762	120.92	313.64	5927.8	1.702
	54I	6-10	197.10	188.90	196.70	194.70	43.98	27.68	71.66	1.588	108.60	(113)	109.17	22,486	0.0746	120.95	313.76	5928.1	1.703
FQ-22	54I	4-8	197.40	189.00	196.90	194.70	44.02	27.66	71.68	1.591	108.80	(114)	109.17	22,495	0.0756	120.96	313.79	5926.8	1.703
	54I	6-10	197.30	188.90	196.90	194.70	43.99	27.66	71.66	1.590	108.80	(114)	109.15	22,500	0.0740	120.95	313.97	5927.0	1.704
FQ-23	54I	6-10	173.90	167.20	177.10	175.30	40.14	25.90	66.05	1.549	109.03	(112)	100.50	20,650	0.0728	121.32	312.65	5939.4	1.694
	54I	18-22	174.00	167.00	177.20	175.20	40.12	25.90	66.02	1.548	109.02		100.44	20,658	0.0688	121.35	312.88	5939.7	1.695
	54I	30-34	174.10	166.80	177.20	175.00	40.05	25.90	65.95	1.546	109.00		100.32	20,655	0.0693	121.39	313.18	5940.2	1.696
	54I	38-42	174.10	166.70	177.30	174.90	39.97	25.89	65.86	1.543	109.00		100.28	20,657	0.0704	121.29	313.59	5940.7	1.698
	54I	50-54	174.20	166.60	177.40	174.90	40.00	25.91	65.91	1.544	109.00		100.11	20,643	0.0727	121.55	313.23	5940.7	1.696
	54I	58-62	174.20	166.43	177.40	174.70	39.99	25.87	65.86	1.546	109.00		100.06	20,632	0.0742	121.55	313.21	5940.3	1.696
	54I	78-82	174.30	166.20	177.50	174.50	39.88	25.86	65.74	1.542	109.00		99.93	20,619	0.0771	121.48	313.65	5941.1	1.698
	54I	90-94	174.40	166.00	177.60	174.40	39.85	25.87	65.72	1.540	109.00		99.85	20,608	0.0782	121.57	313.52	5941.5	1.698
	54I	94-98	174.40	165.90	177.60	174.40	39.88	25.83	65.71	1.544	109.00	(112)	99.79	20,599	0.0785	121.58	313.49	5940.8	1.698

Notes: (1) Chamber pressure measurements are in error by approximately 10 percent (see Section 4.3).
(2) Thrust data were influenced by differential heating.
(3) Values of T_t for firings FQ-20 through 23 were taken from the bottom of the supply tank. All other propellant temperatures in this table were sensed at the flowmeters.

TABLE IV-V
SPECIFIC IMPULSE AS A FUNCTION OF TCV
(Measured Data)

Target Chamber Pressure, psia	Target Propellant Temperature, °F	Vacuum Specific Impulse, I_{sp_v}		
		Mod I-C (Ref. 14)	Mod I-D	Mod I-E
100	30		313.1 (4)	312.9 (2)
	75	313.8 (3)		
	110	314.4 (1)		313.3 (1)
110	30			313.9 (1)
	75	314.3 (1)		
	110	315.1 (2)		313.8 (2)
	117			314.0 (1)
117	75	314.6 (1)		
	110	315.0 (1)		

Notes: (1) All firings are dual-bore TCV operation.

(2) Numbers in parenthesis are number of firings in each group.

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K. L. Farrow, A. L. Berg, and C. E. Robinson, ARO, Inc.

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13. ABSTRACT

Simulated altitude testing of the Apollo SPS Block II engine was conducted to qualify the latest design bipropellant valves (Mod I-D and Mod I-E), to investigate combustion overpressure during ignition, and to determine the heating rates of the flight-type electric heaters on the propellant lines and bipropellant valve. Propellants used were nitrogen tetroxide and 50/50 hydrazine/unsymmetrical dimethylhydrazine. Fifty-one test firings were made for a total of 922 sec of firing time during four test periods. Engine operation and performance were satisfactory. At the conclusion of these tests, the Mod I-E bipropellant valve was considered qualified for flight. Combustion overpressure as high as 27 percent were obtained, and the electric heaters operated satisfactorily.

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Qualification Tests						
Altitude simulation						

1. Project Apollo.
2. Rocket motors --AJ10-137
4. Valves

11-3.

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